Toward an integrated geologic, geochemical, and structural model for formation of the MacLellan Au-Ag and related mineral deposits, Lynn Lake, Manitoba

Evan Carman George Hastie

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Toward an integrated geologic, geochemical, and structural model for formation of the MacLellan Au-Ag and related mineral deposits, Lynn Lake, Manitoba

by

Evan Hastie

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Earth and Environmental Sciences in Partial Fulfillment of the Requirements for the Degree of Master of Science at the University of Windsor

Windsor, Ontario, Canada

2014
Toward an integrated geologic, geochemical, and structural model for formation of the MacLellan Au-Ag and related mineral deposits, Lynn Lake, Manitoba

by

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August 1, 2014
Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

This thesis also incorporates research while under the employ of Carlisle Goldfields Limited under the supervision of Dr. Joel Gagnon and Dr. Iain Samson. This research is covered in chapters 2 and 3 of the thesis. In all cases the key ideas, primary contributions, experimental designs, data analysis, and interpretation, were performed by the author, and the contribution of co-authors primarily through the provision of conceptual understanding and editing.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.
Abstract

The MacLellan deposit and related Au-Ag occurrences reside in the northern portion of the Lynn Lake greenstone belt, Manitoba. All occurrences within the study area contain the same lithologies, alteration styles, and were formed by similar processes.

The Nisku Deposit, Main and Dot Zones contain the most abundant Au-Ag mineralization and are characterized by increased arsenopyrite, galena, and sphalerite relative to other zones. These deposits occur at intersections between D₄ north-northeast striking brittle fault zones and D₂ ≈ 045° striking ductile shear zones. The differences in mineralization styles between individual zones result from the presence or absence of these intersecting D₂-D₄ structures.

Gold and silver mineralization is the result of hydrothermal fluid infiltration along zones of high strain that formed during D₂ and D₄ deformation events. Amphibole-plagioclase schist has been altered by biotite ± quartz ± sulphide mineral alteration (D₂) and Cr-clinochlore + carbonate ± hornblende + quartz alteration (D₄).
Dedication

To BM & BW for loving me and for reading and keeping my first ‘publication’.
To Poppa for helping me hold my cards when I couldn’t.
To Gran for being the greatest matriarch a family could have.
To Joel for believing in me and giving me the greatest opportunity.
To Ali for helping ignite my passion for geology.
To Iain a.k.a. ‘Sir’ for keeping me focused and helping me follow the scientific method.
To Sharon for organizing my life.
To my family for more than I could say.
To my colleagues for their support and help.
To Peter for his teachings in life and in the field.
To Alan for late night calls.
To Sara for late night calls.
To Heather for being my love and muse.
To my mother for everything that makes me who I am.
And most importantly to my father, Carman Hastie, for being the most intelligent person I know.
Acknowledgements

This project would never have been possible without the opportunity and generous financial support given to me by Peter Karelse and Carlisle Goldfields Ltd. along with the thesis supervision and financial support from Dr. Joel Gagnon, and Dr. Iain Samson. Along the way I have also been most fortunate to work alongside colleagues in Lynn Lake and Windsor that have helped me expand my knowledge in the field of geology and in life.

I would like to thank the faculty, staff and students in the Department of Earth and Environmental Sciences and the University of Windsor for always making me feel at home and giving me one of the greatest experiences of my life.
Table of Contents

Declaration of Co-Authorship/Previous Publication ................................................. iv

Abstract .......................................................................................................................... v

Dedication ....................................................................................................................... vi

Acknowledgements .................................................................................................... vii

List of Tables .................................................................................................................. ix

List of Figures ............................................................................................................... x

List of Appendices ....................................................................................................... xiv

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

Bibliography ................................................................................................................ 10

Chapter 2 – The MacLellan deposit and related Au-Ag occurrences, Lynn Lake, Manitoba: products of localized or regional processes? ........... 14

Bibliography ................................................................................................................ 57

Chapter 3 - Lithogeochemical changes accompanying deformation and mineralization in the MacLellan deposit and related Au-Ag occurrences, Lynn Lake, Manitoba: implications for element mobility and deposit genesis .... 61

Bibliography ................................................................................................................ 96

Chapter 4 – Conclusions ............................................................................................. 101

Appendices .................................................................................................................. 106

VITA AUCTORIS ........................................................................................................... 108
List of Tables

Table 1.1 - Magmatic, metamorphic, and structural development and evolution of the Lynn Lake greenstone belt ................................................................. 2
Table 2.1 - Inventory of samples collected from the MacLellan deposits ..........20
Table 2.2 - Summary of structural observations and measurement data .........33
Table 2.3 - Comparison of observed lithologies .............................................48
Table 3.1 - Comparison of lithologies ............................................................64
Table 3.2 - Rock types at the MacLellan deposit (major oxides and LOI) .......75
Table 3.3 - Comparison of lithologies ............................................................84
List of Figures

Figure 1.1 - Regional geology of the Lynn Lake district ............................................. 2

Figure 1.2 - Volcanism, magmatism, sedimentation, metamorphism, and deformation in the Lynn Lake Greenstone Belt ................................................................. 4

Figure 1.3 - Map of the MacLellan deposit and related Au-Ag occurrences showing previous occurrence nomenclature ................................................................. 8

Figure 2.1 - Regional geology map showing Lynn Lake and the MacLellan Au-Ag deposit .........................................................................................................................17

Figure 2.2 - Map of the MacLellan deposit and related Au-Ag occurrences ......17

Figure 2.3 - Map of the MacLellan deposit and related Au-Ag occurrences showing drill hole and outcrop locations .................................................................20

Figure 2.4 – Geological map of the MacLellan deposit and related Au-Ag occurrences .........................................................................................................................24

Figure 2.5 - Hand specimen photographs and photomicrographs of amphibole-plagioclase schist and biotite-quartz schist .................................................................29

Figure 2.6 - Hand specimen photographs and photomicrographs of biotite-banded chlorite-amphibole schist and chlorite-amphibole schist .....................30

Figure 2.7 - Hand specimen photographs and photomicrographs of granite and metagabbro .................................................................................................................31

Figure 2.8 - Common structural elements observed in the study area ..........34
Figure 2.9 - Mylonitic textures seen at the Highway 391 outcrop...............35

Figure 2.10 - Hand specimen and outcrop photographs, and thin section
photomicrographs showing examples of biotite and chlorite/amphibole
alteration ........................................................................................................37

Figure 2.11 - Photomicrographs of Au-Ag occurrences ..............................40

Figure 2.12 - Photomicrographs of Au-Ag occurrences ..............................41

Figure 2.13 - Photomicrographs of various Au and sulphide mineral
relationships under reflected light ...............................................................44

Figure 2.14 - Paragenesis of gold, sulphide and oxide minerals.................45

Figure 2.15 - 3-D image generated from Gemcom™ provided by Carlisle
Goldfields Ltd. combined with approximate scale and landmark locations.....46

Figure 2.16 - Plan view map of the Crown Pillar outcrop showing Au
distribution ....................................................................................................47

Figure 2.17 - Paragenesis of gold, sulphide minerals and oxide minerals ......55

Figure 3.1 - Regional geology map showing Lynn Lake and the MacLellan Au-Ag
deposit .........................................................................................................66

Figure 3.2 - Map of the MacLellan deposit and related Au-Ag occurrences .....66

Figure 3.3 - Map of the MacLellan deposit and related Au-Ag occurrences
showing drill hole and outcrop locations ....................................................69

Figure 3.4 - Geological map of the MacLellan deposit and related occurrences
.....................................................................................................................72
Figure 3.5 - Chondrite-normalized REE (rare earth element) plot ..................76
Figure 3.6 - Chondrite-normalized REE (rare earth element) plot ..................77
Figure 3.7 - Chondrite-normalized REE (rare earth element) plot ..................78
Figure 3.8 - La/Lu vs. Eu/Eu* plot showing rock types at the MacLellan deposit ................................................................................................................................................79
Figure 3.9 - Representative alteration styles observed at the MacLellan deposit .............................................................................................................................................81
Figure 3.10 - Down hole plot of drill hole MG07-02 showing Ni and Cr variation ........................................................................................................................................................................82
Figure 3.11 - LA-ICP-MS spectra overlain on thick section showing Cr in chlorite minerals with laser transects .................................................................................................................................83
Figure 3.12 - Representative rock types observed at the MacLellan deposit and related Au-Ag occurrences showing common textural elements ..................86
Figure 3.13 - Magma series classification plots for amphibole-plagioclase schist ........................................................................................................................................................................87
Figure 3.14 - Isocon and histogram plots showing volume change and elemental gain/loss in rock types .........................................................................................................................92
Figure 3.15 - Isocon and histogram plots showing volume change and elemental gain/loss in rock types .........................................................................................................................93
Figure 3.16 - Isocon and histogram plots showing volume change and elemental gain/loss in rock types .........................................................................................................................94
Figure 3.17 - Isocon and histogram plots showing volume change and elemental gain/loss in rock types ..........................................................95
List of Appendices (page numbers associated with CD)

Appendix I – Drill Hole Logs ................................................................. 2

Appendix II – Sample Breakdown and Au-Ag Analyses ...................... 510

Appendix III – External Lab Results (TSL and ACTLabs) ...................... 516

Appendix IV – Internal Lab Results (SEM-EDS, LA-ICP-MS and XRD) .......... 633

Appendix V – Letter of Permission for Co-authorship ............................ 1155
Chapter 1

Introduction

The geology of the Lynn Lake greenstone belt and of the MacLellan Au-Ag deposit has been previously characterized, however, these investigations have either focused predominantly on the regional geology of the Lynn Lake greenstone belt (e.g., Milligan, 1960; Koo, 1976; Gilbert et al., 1980), were reconnaissance in nature with respect to the mineralized zones (e.g., Fedikow and Gale, 1982; Fedikow, 1986), or addressed in detail only limited areas or aspects of the MacLellan deposit and associated Au-Ag occurrences (e.g., Augsten, 1985; Gagnon, 1991; Fedikow, 1992). To date, an integrated study incorporating the lithology, geochemistry, deformation, mineralization, and alteration across all of the properties that host the MacLellan deposit and related Au-Ag occurrences (i.e., the K, Dot, Rainbow, West, Main, and East zones, and Nisku deposit) has not been undertaken. Inconsistencies in the geologic characterization and the lack of an integrated genetic model for the various occurrences of mineralization, if applicable, have made it difficult in terms of developing and mining the resource, and for exploration for other potential occurrences of similar mineralization along the northern and southern portions of the Lynn Lake greenstone belt.

Regional Geology

The Lynn Lake greenstone belt (LLGB) lies within the Trans-Hudson Orogen in northwestern Manitoba and is Paleoproterozoic in age (Baldwin et al., 1987) (Fig. 1.1). The LLGB is subdivided into Sickle Group and Wasekwan Group major stratigraphic assemblages (Milligan, 1960). Metamorphosed volcanic, sedimentary, and plutonic rocks comprise the Wasekwan Group (Bateman, 1945), and these rocks are unconformably overlain by metamorphosed sandstone and conglomerate of the Sickle Group (Norman, 1933). The Wasekwan Group has been further subdivided into two, approximately east-west trending lithostructural belts, named the Northern and Southern Belts, which are dominated by mafic metavolcanic rocks
(Gilbert et al., 1980). Wasekwan Group rocks of the LLGB were interpreted by Gilbert et al. (1980) to have undergone five separate regional deformation events and to have experienced low to middle amphibolite facies metamorphism (Table 1.1).

![Regional geology of the Lynn Lake district](modified from Beaumont-Smith and Böhm, 2006).

<table>
<thead>
<tr>
<th>Lynn Lake Greenstone Belt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YOUNEST</strong></td>
</tr>
<tr>
<td>Northwest faulting (e.g., seen at Lynn Lake)</td>
</tr>
<tr>
<td><strong>D₅:</strong></td>
</tr>
<tr>
<td>Foliation development and cataclasis (north-easterly trending?)</td>
</tr>
<tr>
<td>Open cross folding</td>
</tr>
<tr>
<td>Felsic intrusion (e.g., Burge Lake granite – Rb/Sr whole rock age 1765 ± 100 Ma)</td>
</tr>
<tr>
<td>Localized retrograde metamorphism</td>
</tr>
<tr>
<td><strong>D₄:</strong></td>
</tr>
<tr>
<td>East and north-easterly trending shearing and faulting (e.g., seen at Cartwright Lake)</td>
</tr>
<tr>
<td>North- and east-trending basins and domes (i.e., seen at Hughes Lake)</td>
</tr>
<tr>
<td>Regional metamorphism and foliation development</td>
</tr>
<tr>
<td>Mafic to felsic intrusion (e.g., seen at Laurie Lake)</td>
</tr>
</tbody>
</table>
D₃:
Thrust faulting at belt margins (e.g., seen at Tod Lake)

Mafic intrusion (e.g., Black Trout Lake diorite)

**Sickle Group:**
Shallow water, terrestrial sedimentation

D₂:
Uplift, erosion, faulting, and tilting
Felsic intrusion (e.g., Hughes Lake – Rb/Sr whole rock age 1940 ± 75 Ma, 1825 ± 210 Ma)
Mafic intrusion (e.g., Lynn Lake gabbro?)

D₁:
East-northeast trending folding and faulting

**Wasekwan Group:**
Mafic to felsic intrusion
Mafic to felsic tholeiitic and calc-alkaline volcanism
Felsic volcanism, faulting, and sedimentation
Mafic tholeiitic volcanism

**OLDEST**

<table>
<thead>
<tr>
<th>Table 1.1.</th>
<th>Magmatic, metamorphic, and structural development and evolution of the Lynn Lake greenstone belt (modified from Gilbert et al., 1980). Whole rock age dates contained in the table are taken from Clark (1980).</th>
</tr>
</thead>
</table>

Re-examination of the regional structural geology by Beaumont-Smith and Böhm (2002) resulted in the addition of a sixth, regional deformation event (Fig. 1.2), and U-Pb age-dating of prismatic, euhedral, zircon crystals revised the age for the Lynn Lake rhyolite, which is hosted by the Wasekwan Group of the Northern LLGB, from 1910 Ma ± 15 Ma (Baldwin et al., 1987) to 1892 ± 3 Ma. U-Pb isotopic age dating of the Burge Lake granodiorite yielded an age of 1857 ± 2 Ma, which has been interpreted as the minimum age for regional D₂ deformation by Beaumont-Smith et al. (2006).
Local Geology

The MacLellan Au-Ag deposit is located approximately 7 km northeast of the town of Lynn Lake, Manitoba (380994m E, 6307600m N) (Fig. 1.1). Fedikow and Gale (1982) interpreted the host rocks to the MacLellan Au-Ag mineralization to be metamorphosed, fine-grained, tuffaceous, clastic, and chemical sedimentary rocks, interbedded with metamorphosed and variably altered basalts. The metasedimentary units were interpreted to host the majority of the sulphide minerals and, consequently, the Au-Ag mineralization comprising the deposit, and the penetrative foliation of the area was interpreted to be regionally parallel to the layering of the metasedimentary units (Fedikow and Gale, 1982). Fedikow (1986) further described the host rocks to the mineralization and classified them as metamorphosed siltstones, iron formations, and high Mg-Ni-Cr basaltic flows (picrites) and tuffs that had been altered to varying degrees by biotization, silicification, carbonatization, and chloritization.
Gagnon (1991) used more descriptive mineralogical nomenclature, lithogeochemistry, and petrography during a focused study of the Main Zone of the MacLellan Au-Ag deposit. Three, amphibolite grade metamorphic rock types were identified as dominating the Main Zone lithologies: chlorite-hornblende schist, biotite-plagioclase schist, and chlorite-quartz schist. Chlorite-hornblende schist is equivalent to rocks described by Fedikow (1986) as picrites, and biotite-plagioclase schist is equivalent to rocks previously considered to be metasediments and altered, porphyritic metabasalts. The chlorite-quartz schist was considered by Gagnon (1991) to be the product of relatively late, hydrothermal alteration of biotite-plagioclase schist and picritic rocks described by Fedikow (1986). Gagnon (1991) identified three modes of occurrence of Au-Ag mineralization in the Main Zone of the MacLellan deposit:

1. Pyrite-pyrrhotite disseminations and stringers with relatively low-grade Au-Ag mineralization associated with highly deformed quartz veins and biotite ± garnet alteration (QBS veins).
2. Relatively undeformed, subvertical, planar arsenopyrite-quartz replacement veins with relatively high-grade Au-Ag mineralization (Apy-Qtz veins).
3. Large, white ‘flat’ veins associated with late brittle-ductile faulting (i.e., the ‘North Shear’) that were only mineralized where they crosscut the other two, earlier-formed vein sets (i.e., sulphide and Au-Ag appeared to have been locally remobilized into these veins).

Gagnon (1991) did not identify a primary sedimentary unit that was host to syngenetic Au-Ag mineralization as interpreted by Fedikow (1986). Gold-silver mineralization was interpreted to be epigenetic in origin, and associated with zones of high strain, quartz-sulphide veins, and associated hydrothermal (primarily biotite) alteration (Gagnon, 1991). Petrographic, mineralogical, and geochemical studies by Samson & Gagnon (1995) indicated that the stratiform nature of the MacLellan Au-Ag deposit did not reflect syngenetic-exhalative deposition. The tabular nature of the mineralization was interpreted to result from emplacement of vein and replacement-type ore bodies whose geometry was controlled by the metamorphic fabric of the host rocks or resulted from transposition of veins into
subparallelism with the regional foliation due to deformation or emplacement along high strain zones oriented sub-parallel to the regional foliation. The relatively late timing and high temperatures inferred from alteration minerals associated with the Apy-Qtz vein stage of Au-Ag mineralization required a deep-crustal or magmatic fluid source (Samson and Gagnon, 1995).

Fedikow (1992) performed a lithogeochemical comparison to determine if what had initially been interpreted to be metasedimentary rocks were actually highly altered metabasalts. The results of this investigation, however, were inconclusive (i.e., did not identify significant compositional differences between the two rock types).

Ma and Beaumont-Smith (2001) studied the stratigraphy and deformation of the ‘Agassiz Metallotect’ (i.e., the host rock sequence to the MacLellan Au-Ag deposit), and identified six deformation events (D1 to D6). The Au-Ag mineralization was suggested to have an epigenetic, synshear origin (D2) in the MacLellan deposit, although remobilization of syngenetic Au-Ag was not ruled out (Ma and Beaumont-Smith, 2001). Park et al. (2002) performed a regional structural and stratigraphic study of the ‘Agassiz Metallotect’, which identified only four (D1 to D4) of the six regional deformation events previously thought to have affected the Lynn Lake area (cf. Beaumont-Smith and Böhm, 2002). The Au-Ag mineralization at the MacLellan deposit was indicated to be ‘lithology sensitive’, rather than structurally controlled, but no specific evidence or explanation was provided to characterize or support this interpretation (Park et al., 2002).

**Statement of the Problem**

The geology, structure, and mineralization of all of the properties encompassing the MacLellan deposit and related Au-Ag occurrences (K, Dot, Rainbow, West, Main, and East zones, and Nisku deposit) have not been consistently characterized in relation to one another and no attempts have been made to compare and contrast the Au-Ag occurrences (Fig. 1.4). Former exploration and mining activities separated the individual occurrences into distinct zones that were independently characterized, which resulted in different geologic characterizations
and interpretations, and prohibits meaningful comparison between the Au-Ag occurrences. Consistent evaluation of the geology, structure, and mineralization across the occurrences is critical in determining the similarity, if any, in the genesis of the mineralized zones and their association relative to specific regional lithologic units and structures.

The MacLellan Au-Ag deposit has been described as being primarily syngenetic in origin, with minor, secondary remobilization (Fedikow, 1986), and as epigenetic in origin, and associated primarily with deformed, quartz and sulphide veins with biotite alteration that are hosted in high strain zones (Gagnon, 1991, Samson and Gagnon, 1995). The model of Fedikow (1986) requires that a Au-Ag-bearing primary exhalative unit be present, whereas the model of Gagnon (1991) requires that Au-Ag mineralization is associated with veins and associated alteration, within high strain zones. The nature and origin of the other Au-Ag occurrences included in this study (Fig. 1.4) are known either only on a reconnaissance level or are entirely unknown, therefore, examination of these occurrences in the context of the models that have been proposed for the MacLellan Au-Ag deposit is impossible.
Figure 1.3. Map of the MacLellan deposit and related Au-Ag occurrences showing previous occurrence nomenclature.

Exploration activities incorporating all of the Au-Ag occurrences conducted by Carlisle Goldfields Ltd. since 2008 have identified inconsistencies in the numbers and types of lithologies previously identified within the mineralized zones. Characterization of the host rocks and identification of the protoliths to the MacLellan deposit and related Au-Ag occurrences is critical in order to be able to prepare consistent and accurate geologic maps and interpretations, and to enable accurate correlation of the host rock sequence to the MacLellan Au-Ag deposit with the regional geology of the Lynn Lake greenstone belt. Identification and characterization of the temporal and spatial relationships between the different styles of alteration and Au-Ag mineralization, if any, are required in order to use the chemical and mineralogical changes associated with Au-Ag mineralization as potential vectors to locate previously unidentified occurrences of similar mineralization elsewhere.

The number of deformation events that have affected the host rocks to the MacLellan deposit (four events) and related Au-Ag occurrences differs from interpretations based on regional geology (six events). It is critical to determine the
relationships between the structures produced by the different deformation events and Au-Ag mineralization, if any, in order to determine how Au-Ag may have been deposited or subsequently redistributed. These relationships may also prove useful as indicators of similar types of Au-Ag mineralization elsewhere within the Lynn Lake greenstone belt.

If consistent relationships exist between lithology, alteration, structure, and Au-Ag mineralization, then it should be possible to develop an integrated conceptual model for the mineralization that will consistently identify critical indicators of mineralization and reliably apply them across all of the occurrences of mineralization. This will provide benefits to ongoing development activities within the MacLellan deposit and related Au-Ag occurrences, and in exploration for similar occurrences of mineralization elsewhere along the Lynn Lake greenstone belt.

**Research Objectives**

The overall objective of this study is to use new and historical geological, mineralogical, structural, and chemical data to contribute to an improved, integrated genetic model for the MacLellan deposit, and, if appropriate, the other related Au-Ag occurrences. To achieve this overall objective, the following research questions will be addressed:

1. Do similarities exist between the MacLellan deposit and related Au-Ag occurrences that occur on a scale that enables correlation between lithology, alteration, and structure across all of the mineralized zones?
2. What are the host rocks to the MacLellan deposit and related Au-Ag occurrences, what were their igneous or sedimentary protoliths, and is there a relationship between a particular lithology and Au-Ag mineralization?
3. Are the different stages and styles of mineralization in the MacLellan deposit and related Au-Ag occurrences related to particular deformation events and, if so, what is the relationship?
4. What types of alteration occur in the MacLellan deposit and related Au-Ag occurrences, and is there any relationship between a particular style of alteration and mineralization?

5. How does the combination of host rock lithology/protolith, alteration, and structure control the distribution of mineralization in the MacLellan deposit and related Au-Ag occurrences?

References


Chapter 2 – The MacLellan deposit and related Au-Ag occurrences, Lynn Lake, Manitoba: products of localized or regional processes?

Introduction

The geology of the Lynn Lake greenstone belt (Fig. 2.1), and the MacLellan deposit and other associated Au-Ag occurrences (i.e., K, Dot, Rainbow, West, Main, and East zones and the Nisku deposit; Fig. 2.2) have been previously studied (e.g., Milligan, 1960; Koo, 1976; Gilbert et al., 1980; Fedikow and Gale, 1982; Augsten, 1985; Fedikow, 1986; Gagnon, 1991; Fedikow, 1992; Samson and Gagnon, 1995; Samson et al., 1999; Park et al., 2002; Beaumont-Smith and Böhm, 2002; Beaumont-Smith and Böhm, 2003; Beaumont-Smith and Böhm, 2004; Beaumont-Smith et al., 2006). These investigations, however, have focused predominantly on the regional geology of the Lynn Lake greenstone belt (Milligan, 1960; Koo, 1976; Gilbert et al., 1980), were reconnaissance in nature with respect to some of the mineralized zones (Fedikow and Gale, 1982; Fedikow, 1986), or addressed in detail only limited aspects of individual Au-Ag occurrences (Augsten, 1985; Gagnon, 1991; Fedikow, 1992). To date, an integrated study incorporating the petrology, geochemistry, deformation, mineralization, and alteration across all of the properties that host the MacLellan Au-Ag deposit and related occurrences, hereafter referred to as the MacLellan deposits, has not been undertaken.

Previous exploration and mining activities conducted by numerous companies over an extended time period (~ 1950s to 1990s) characterized the MacLellan deposits independently of one another. This has resulted in disparate descriptions of the geology and interpretations of the genesis of the occurrences, and has rendered comparisons of the deposits largely impossible. Consequently, similarities in the geology and genetic relationships between the various Au-Ag deposits, if any, are presently unknown. Observations from drilling programs conducted by Carlisle Goldfields Ltd. from 2011 to 2013, however, indicate that the various Au-Ag occurrences appear to be more similar than previously documented, and a comprehensive study of all of the deposits is required to determine whether
the various mineralized zones are related and to place the occurrences within the context of what is presently known about the regional geology, metamorphism, and deformation of the Lynn Lake greenstone belt.

Fedikow and Gale (1982) described the host rocks to the East, Main, and Rainbow Zones of the MacLellan deposits as metamorphosed, fine-grained, tuffaceous, clastic, and chemical sedimentary rocks, interbedded with metamorphosed and variably altered basalts. The metasedimentary units were interpreted to host the majority of the sulphide minerals and Au-Ag mineralization in the deposits (Fedikow and Gale, 1982). Fedikow (1986) described the host rocks to the mineralization as metamorphosed siltstones, iron formations, and high Mg-Ni-Cr basaltic flows (picrites) and tuffs that had been altered to varying degrees by biotization, silicification, carbonatization, and chloritization. Gold mineralization was described as being primarily syngenetic in origin (i.e., seafloor exhalative) with secondary remobilization during subsequent deformation and metamorphism (Fedikow, 1986).

Gagnon (1991) and Samson and Gagnon (1995), in a focused study of the Main Zone of the MacLellan deposit, identified three, dominant, amphibolite-grade metamorphic rock types as hosts to the mineralization: chlorite-hornblende schist, biotite-plagioclase schist, and chlorite-quartz schist. Chlorite-hornblende schist is equivalent to picrite, and biotite-plagioclase schist is equivalent to metasediments and altered, porphyritic metabasalt described by Fedikow (1986). Chlorite-quartz schist was considered by Gagnon (1991) to be the product of relatively late, hydrothermal alteration of the biotite-plagioclase schist and picritic rocks described by Fedikow (1986). Gagnon (1991) and Samson and Gagnon (1995) did not identify a primary, syngenetic, Au- and Ag-bearing sedimentary unit as suggested by Fedikow (1986), but rather interpreted Au-Ag mineralization to be epigenetic in origin, and associated with zones of high strain, quartz-sulphide mineral veins, and hydrothermal (primarily biotite) alteration (Gagnon, 1991; Samson and Gagnon, 1995). A lithogeochemical study by Fedikow (1992) could not conclusively differentiate between what were interpreted by Fedikow (1986) to be metamorphosed sedimentary rocks (i.e., biotitic siltstones) and basalts, indicating
that the former may be the altered and deformed equivalent of the latter (cf. Gagnon, 1991).

Regional structural mapping of the Lynn Lake greenstone belt by Beaumont-Smith and Böhm (2002) resulted in identification of six deformation events (D₁ to D₆), and U-Pb isotopic age dating of the Burge Lake granodiorite yielded an age of 1857 ± 2 Ma, which is interpreted to be the minimum age for the regional D₂ deformation event identified by Beaumont-Smith et al. (2006). Park et al. (2002), in a structural and stratigraphic study of the MacLellan deposit, identified only four (D₁ to D₄) of the six regional deformation events thought to have affected the Lynn Lake area and concluded that Au-Ag mineralization was 'lithology sensitive', rather than structurally controlled, however, no specific evidence was provided to support this interpretation. Gagnon (1991) and Samson and Gagnon (1995) interpret the timing of Au mineralization to be during and after the D₂ shearing event.

During surface exploration and drilling activities performed by Carlisle Goldfields Ltd. beginning in 2011, it became apparent that previous geologic and structural interpretations were inadequate to enable correlation between lithologic units and structural features, both within and between the individual Au-Ag occurrences. Therefore, consistent characterization of the lithologies, mineralization, alteration, and deformation across all of the properties was necessary in order to develop a comprehensive geologic interpretation that could be used to identify the nature and origin of Au-Ag mineralization across the deposits, and to target new, potentially prospective areas. Chapter 2 presents the results of an investigation of the MacLellan deposit and related Au-Ag occurrences, and provides new field, textural, and lithogeochemical observations pertaining to the host rocks and Au and Ag mineralization-related deformation and alteration. The following questions, which are intended to assess potential geologic and genetic relationships at a sufficient scale to enable comparison between the various Au-Ag occurrences, will be addressed in this chapter:
Figure 2.1. Regional geology map showing Lynn Lake and the MacLellan Au-Ag deposit (modified from Beaumont-Smith and Böhm, 2006).

Figure 2.2. Map of the MacLellan deposit and related Au-Ag occurrences showing previous occurrence nomenclature.
1. Do the MacLellan deposit and related Au-Ag occurrences have similar host lithologies, mineralization styles, alteration types, and structure? A comparison of the geology across all occurrences will determine whether or not there is a consistent relationship between the mineralization and specific lithologies or geologic features.

2. What are the host rocks to the Au-Ag mineralization in the MacLellan deposit and related occurrences, and is there a relationship between a particular lithologic unit or units and mineralization? If a particular lithologic unit or units and Au-Ag mineralization are spatially and temporally associated, then consistent field, textural, and geochemical evidence of this relationship should exist.

3. Are the mineralization styles present in the MacLellan deposit and related Au-Ag occurrences related to particular deformation events and structures and, if so, what is the relationship? If a specific deformation event and Au-Ag mineralization are spatially associated, then this relationship should be evident from field relationships (1:2400 structural mapping), lithogeochemical analysis, and microstructural analysis.

4. What are the mineralization styles and associated alteration types present within the MacLellan deposit and related Au-Ag occurrences, and is there a relationship between a particular alteration type and Au-Ag mineralization? If a spatial correlation exists between an alteration type and Au-Ag mineralization, then this relationship should be evident from field relationships (1:2400 lithologic mapping), petrography, and lithogeochemical analysis.

The study area included all properties northeast of the town of Lynn Lake, Manitoba where Au and Ag occurrences have been previously documented (i.e., K, Dot, Rainbow, West, Main, East zones, and Nisku deposit; Fig. 2.2). Inclusion of all of the known Au-Ag occurrences enabled comparisons between the deposits to determine whether they represent the unique products of isolated and distinct
geologic processes that affected only relatively small areas, or are all products of regional geologic processes that affected relatively large areas. The study area is delimited by exploration claims held by Carlisle Goldfields Ltd. and is of sufficient size to enable comparison with previous mineral deposit studies (e.g., Augsten, 1985; Gagnon, 1991; Fedikow, 1992; Samson and Gagnon, 1995; Park et al., 2002), as well as regional and reconnaissance geologic and structural mapping studies (e.g., Milligan, 1960; Koo, 1976; Gilbert et al., 1980; Beaumont-Smith and Böhm, 2002; Beaumont-Smith and Böhm, 2003; Beaumont-Smith and Böhm, 2004; Beaumont-Smith et al., 2006).

**Methodology**

*Drill Core and Outcrop Description and Sampling*

The majority of the samples used in this study were collected from drill core that was obtained during exploration programs performed by Carlisle Goldfields Ltd. between 2011 and 2013. Approximately 32,857 m of drill core was logged for this purpose and, in most cases fresh samples were obtained from drill core due to weathering effects and the lack of extensive outcrop in the study area. In total, 206 samples comprising approximately 1 kg of rock each were collected from the MacLellan deposits (Table 2.1). Of the 206 rock samples, 184 unoriented samples were collected from 26 of the 68 drill holes distributed across the study area (Fig. 2.3). In addition, 22 oriented samples were obtained from 6 of the 12 outcrops located within the study area (Fig. 2.3) and an additional 3 outcrops located on properties to the east of the study area. Outcrops were mapped in detail at a scale of 1:50, and detailed lithologic, mineralogic, textural, and structural data were obtained. Trench sampling performed in 2008 by Carlisle Goldfields Ltd. across the ‘Crown Pillar’, which is an approximately 50 by 120 m stripped area located immediately over the MacLellan Main Zone deposit (Fig. 2.3 and 2.15), provided high resolution (0.3 to 1.5 m) Au-Ag assay data from 395 samples in addition to
detailed lithologic, mineralogic, textural, and structural information.

Figure 2.3. Map of the MacLellan deposit and related Au-Ag occurrences showing drill hole and outcrop locations.

<table>
<thead>
<tr>
<th>Drill Hole/Outcrop ID</th>
<th>Easting (UTM)</th>
<th>Northing (UTM)</th>
<th>Samples Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG11-02</td>
<td>380578</td>
<td>6307157</td>
<td>6</td>
</tr>
<tr>
<td>MG11-04</td>
<td>380353</td>
<td>6307390</td>
<td>4</td>
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<td>MG11-05</td>
<td>380304</td>
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<td>380461</td>
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<td>6</td>
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<tr>
<td>MG11-10</td>
<td>380402</td>
<td>6307482</td>
<td>12</td>
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<td>MG11-11</td>
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<td></td>
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<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>---------</td>
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<tr>
<td>MG11-14</td>
<td>380727</td>
<td>6307854</td>
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</tr>
<tr>
<td>MG11-15</td>
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<td>MG11-16</td>
<td>380258</td>
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<tr>
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<td>381170</td>
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<td>380463</td>
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<tr>
<td>Rushed Showing</td>
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<td>Highway Outcrop</td>
<td>377371</td>
<td>6304575</td>
<td>7</td>
</tr>
<tr>
<td>Trench Outcrop</td>
<td>381410</td>
<td>6308087</td>
<td>3</td>
</tr>
<tr>
<td>Crown Pillar</td>
<td>380945</td>
<td>6307472</td>
<td>2</td>
</tr>
<tr>
<td>Stripped outcrops (3) (= 1.5 km SSW of study area)</td>
<td>383384</td>
<td>6306416</td>
<td>5</td>
</tr>
<tr>
<td>Outcrop Near MG11-24 Collar</td>
<td>379973</td>
<td>6307114</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.1. Inventory of samples collected from the MacLellan deposits. Only drill holes and outcrops from which samples were collected are listed.

Rock types, ductile and brittle shear zones, folds, veins, alteration, and mineralization were identified and described during drill core logging and, where possible, spatial orientation data were also obtained. Representative drill core samples were collected of least altered and altered rocks, veins, alteration, and mineralization. In most cases, samples were used for multiple purposes to enable correlation between lithology, alteration, deformation and Au-Ag mineralization and
to provide the maximum amount of information from the samples that were collected.

**Petrographic Analysis and Mineral Identification**

Eighty-six polished thin and 91 polished thick sections were prepared from outcrop and drill core samples by Vancouver Petrographics Ltd. These sections were selected for detailed characterization of lithology, mineralogy, texture, alteration, deformation, and Au-Ag mineralization. Thick and thin sections were photographed and their mineralogy and textures were characterized using an Olympus BX51 polarizing transmitted and reflected light petrographic microscope. In some cases, mineral identification was aided using compositional information obtained using an FEI Quanta® 200f field emission scanning electron microscope (SEM) coupled with an EDAX® energy dispersive spectroscopy (EDS). Details of the samples and thin sections and analytical instrumentation operating conditions are provided in Appendix II and IV respectively.

**Whole-rock Chemical Analysis**

Fifty samples, representing least altered and altered equivalents, were selected for whole rock geochemical analyses to aid in lithologic identification and to quantify compositional changes resulting from Au-Ag mineralization and related alteration. The analyses were performed by ACTLabs in Ancaster, Ontario and included major element oxides (SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MnO, MgO, CaO, Na$_2$O, K$_2$O, TiO$_2$, and P$_2$O$_5$) and minor and trace elements (Sc, Be, V, Cr, Co, Ni, Cu, Zn, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, In, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Tl, Pb, Bi, Th and, U) using lithium metaborate/tetraborate fusion followed by digestion and analysis using inductively-coupled plasma mass spectrometry (ICP-MS). In addition, Au and Ag concentration data for all drill core and Crown Pillar trench samples were obtained using fire assay analysis by TSL Laboratories, Saskatoon, Saskatchewan. Sixty-four samples were also analyzed for As and Sb concentrations using ICP optical emission spectroscopy (OES) by TSL.
Laboratories. The results of the whole rock ICP-MS, ICP-OES, and fire assay analyses are provided in Appendix III.

**Sulphide Mineral Elemental Microanalysis**

Seven thick sections, prepared from rocks containing representative assemblages of sulphide minerals and significant concentrations of Au and Ag based on fire assay analysis, were analyzed using laser ablation (LA)-ICP-MS at the Great Lakes Institute for Environmental Research (GLIER) at the University of Windsor, Ontario. Forty-one individual LA-ICP-MS mineral analyses were conducted to determine the trace element content of Au-Ag alloys and the occurrence of Au and Ag within and associated with the major sulphide minerals identified within the deposits (Py, Po, Apy, Ccp, Gn, and Sp). Operating conditions of the laser and mass spectrometer and results of the LA-ICP-MS analyses are provided in Appendix IV.

**Results**

**Lithologic Units and Field Relationships**

Based on detailed outcrop mapping and drill core logging, the major mappable lithologic units that were identified in the study area are: 1) amphibole-plagioclase schist, 2) biotite-quartz and quartz-biotite schist, 3) biotite-banded chlorite-amphibole schist, 4) chlorite-amphibole schist, 5) granite, and 6) metagabbro. With the exception of granite and metagabbro, these lithologies have gradational contacts with one another and are repetitive within the deposit host rock sequence (Fig. 2.4). Metagabbro has only been observed in places in drill core and, therefore, does not appear on the map due to the small scale.
Figure 2.4. Geological Map of the MacLellan Au-Ag deposit and related occurrences showing lithological units.
**Amphibole-Plagioclase Schist**

A weakly foliated rock that occurs in units with meter- to kilometer-scale thicknesses that can be traced along strike for several kilometers. Amphibole crystals define the weak foliation, which strikes approximately 45° and has an approximately vertical dip (85 to 90°). This fine-grained, dark green (in hand specimen) rock comprises 70 to 75 modal percent subhedral hornblende ± actinolite, 20 to 25% subhedral, relict plagioclase phenocrysts, less than 5% anhedral, interstitial quartz, and approximately 1% disseminated, equant magnetite (Fig. 2.5A, B, C). The relict plagioclase phenocrysts range in size from 1 to 5 mm and the groundmass minerals from 250 to 500 μm. This rock type is the most abundant lithology, comprising nearly 50% of the study area (Fig. 2.4). With the exception of the granite and metagabbro, this rock is also the least deformed and altered of the host rocks, and is best represented outside of areas of high strain and hydrothermal alteration, particularly within the extreme northern and southern portions of the study area (Fig. 2.4).

**Biotite-Quartz Schist**

Biotite-quartz schist is a strongly foliated rock that occurs in units varying in thickness from 1 to 100 m and can be traced along strike for distances up to approximately one kilometer. Biotite-quartz schist predominantly displays the dominant S_n foliation (striking approximately 45° and dipping almost vertically), which is defined by aligned biotite crystals. This fine-grained, black (in hand specimen) rock comprises 45 to 55%, strongly foliated, platy biotite aggregates, and 45 to 55%, subhedral, quartz grains that occur with 0 to 2% deformed, relict plagioclase phenocrysts, 0 to 2% euhedral to subhedral garnet crystals, and up to 1%, disseminated, equant magnetite and acicular ilmenite (Fig. 2.5D, E, F). The biotite crystals range from 0.1 to 5 mm in length, quartz from 0.1 to 1 mm, plagioclase from 0.25 to 1 mm, garnet from 1 mm to 2 cm, and magnetite and ilmenite from 50 to 500 μm. In some localities, quartz is more abundant than biotite but, for simplicity, these rocks are all referred to as biotite-quartz schist. This lithology occurs repetitively within, and comprises a significant (approximately
15%) proportion of the host rock sequence to the MacLellan deposits. Biotite-quartz schist occurs only in areas exhibiting the highest degrees of strain as evidenced by deformation of relict plagioclase crystals, which are observed in all lithologies except granite and metagabbro. These plagioclase crystals are, in places, stretched and elongated parallel to the dominant S_n foliation, which is evident throughout the study area, with the exception of where it has been obscured by subsequent deformation or alteration. Where a high degree of strain is observed in outcrop (Fig. 2.8A), amphibole crystals and relict plagioclase phenocrysts are finer grained and are more elongated where biotite is also present. The biotite in biotite-quartz schist shows evidence of growth around and replacement of elongated amphibole and plagioclase crystals and does not display signs of an earlier strain event. Indicators of this type of strain (elongated amphibole and plagioclase crystals) are boudins, sigma and delta clasts, and mylonitic textures (Table 2.3 and Fig. 2.8). Biotite-quartz schist has gradational contacts with biotite-banded chlorite-amphibole schist and chlorite-amphibole schist.

**Biotite-Banded Chlorite-Amphibole Schist**

This lithology occurs at the contact between, and is gradational with, units of biotite-quartz schist and chlorite-amphibole schist, and exhibits evidence of moderate to high degrees of strain, as evidenced by deformation of relict plagioclase crystals that occur as boudins, sigma and delta clasts, and have mylonitic textures (Table 2.3 and Fig. 2.8A). This lithology occurs in units that vary in thickness from 1 to 200 m and can be traced along strike for distances up to approximately 1.5 km. Biotite-banded chlorite-amphibole schist displays the dominant S_n foliation (striking approximately 45° and dipping 85 to 90°), with oriented biotite and amphibole crystals defining the foliation. In some places, a crenulation cleavage is present, indicating the presence of an S_{n+1} deformation event. This rock is a fine- to coarse-grained, green- and black-banded (in hand specimen) rock, comprising 30 to 60%, subhedral, intergrown hornblende ± actinolite crystals within a matrix of 30 to 60% chlorite crystals, and 10 to 15%, foliation-parallel bands (0.1 to 1 m scale) of unfoliated and foliated, platy biotite crystals, with up to 2% relict, deformed
plagioclase phenocrysts, and up to 1%, disseminated equant magnetite and acicular ilmenite crystals (Figure 2.6A, B, C). Hornblende and actinolite crystals range from 0.5 to 1 cm in length, biotite from 0.1 to 5 mm, plagioclase from 0.25 to 2 mm, and chlorite from 50 to 500 μm. Biotite-banded chlorite-amphibole schist comprises approximately 20% of the host rock sequence, always occurs between units of biotite-quartz schist and chlorite-amphibole schist, and was only observed in areas showing moderate to high degrees of strain.

**Chlorite-Amphibole Schist**

Chlorite-amphibole schist is a weakly to strongly foliated rock that occurs in repetitive units with thicknesses varying from 1 to 250 m, is continuous along strike for 100s of meters, and exhibits gradational contacts with amphibole-plagioclase schist (Fig. 2.4). Aligned amphibole crystals define the dominant $S_n$ foliation, which strikes approximately $45^\circ$ and has an approximately vertical dip ($85$ to $90^\circ$). In some places, a crenulation cleavage is present, indicating the presence of an $S_{n+1}$ deformation event. This coarse- to fine-grained, green (in hand specimen) rock comprises 30 to 70%, subhedral, intergrown hornblende and actinolite crystals within a matrix of 30 to 70% chlorite crystals, containing up to 2% relict, deformed plagioclase phenocrysts, and up to 2%, disseminated, equant magnetite and acicular ilmenite crystals (Fig. 2.6D, E, F). The hornblende and actinolite crystals range from 0.5 to 1 cm in length, the plagioclase from 0.5 to 2 mm, and chlorite from 50 to 500 μm. This lithology comprises approximately 25% of the host rock sequence and was only observed in areas showing medium to high degrees of strain (Fig. 2.4).

**Granite**

Numerous, meter-sized dykes of granite intrude into units of amphibole-plagioclase schist in the northwestern portion of the study area, in the vicinity of Dot Lake (Fig. 2.4). This unmetamorphosed and relatively undeformed lithology exhibits clear intrusive contacts with the other host rock lithologies, however, chilled margins were not observed. This lithology corresponds to the intrusive suite identified as the Burge Lake granite/granodiorite (Beaumont-Smith et al., 2006), which is an
approximately 5 by 15 km pluton, which is centred at a location north-northwest of the MacLellan deposit. The granite is coarse-grained, comprises 40 to 50% subhedral, potassium feldspar, 30 to 40% subhedral, plagioclase grains, and 30 to 40% subhedral quartz that are all 0.1 to 1 cm in size, with up to 5%, irregular, subhedral biotite crystals that are 0.5 to 1 mm in size (Fig. 2.7A, B, C). Semi-massive (30 to 50%) pyrrhotite was observed in outcrop and drill core at the contact between the granite and the other lithologies.

**Metagabbro**
Metagabbro was observed only in core and occurs as meter-sized intrusives that are relatively minor (less than 2% of the sequence), but are mappable across adjacent drill holes (up to 100 metres apart). This coarse-grained, metamorphosed, dark green (in hand specimen) rock comprises 45 to 50% subhedral, intergrown hornblende crystals, 30 to 35% subhedral plagioclase crystals, 15 to 20% unfoliated platy biotite crystals, which have partially replaced hornblende, and 0 to 5%, subhedral, interstitial quartz crystals (Fig. 2.7D, E, F). The hornblende and biotite crystals range from 0.1 to 1 mm in length and the plagioclase and quartz crystals from 100 to 500 μm. This lithology displays stretching and elongation of mineral grains along contacts with other host rock lithologies, however, chilled margins were not observed.
Figure 2.5. Hand specimen photographs and photomicrographs of amphibole-plagioclase schist (A, B, and C) and biotite-quartz schist (D, E, and F). (B) and (C) together and (E) and (F) together are the same photomicrographs under plain polarized light and crossed polars.
Figure 2.6. Hand specimen photographs and photomicrographs of biotite-banded chlorite-amphibole schist (A, B, and C) and chlorite-amphibole schist (D, E, and F). (B) and (C) together and (E) and (F) together are the same photomicrographs under plain polarized light and crossed polars.
Figure 2.7. Hand specimen photographs and photomicrographs of granite (A, B, and C) and metagabbro showing strained quartz and plagioclase (D, E, and F). (B) and (C) together and (E) and (F) together are the same photomicrographs under plain polarized light and crossed polars.

**Deformation**

The textures and structures identified in outcrop, drill core, and thin section at the MacLellan deposit and related Au-Ag occurrences indicate that up to four deformation events (D₁ to D₄) have affected the study area. These events can be
separated based on crosscutting relationships, which can be used to establish the relative timing of the various deformation events. The deformation event that produced the most dominant, widely distributed features throughout the study area (D_n) is characterized by ductile structures (L_s, F_n, sigma clasts, delta clasts, mylonitic textures, and S-C fabrics; Table 2.2 and Figs. 2.8 and 2.9) and foliation (S_n), which is defined predominantly by aligned biotite and amphibole crystals. This dominant foliation (S_n) occurs in all rock types except granite and metagabbro. The degree of strain exhibited by relict plagioclase phenocrysts (i.e., stretching to varying degrees) was also observed in all rock types except granite and metagabbro. The highest degree of strain shown by these relict plagioclase phenocrysts occurs in rocks that also contain the greatest proportions of biotite.

All other deformation events and associated structures are described relative to the main deformation event (e.g., D_n). The characteristics of the various deformation features and their relative timing are presented in Table 2.2. Examples of the most relevant structures can be found in Figure 2.8.

<table>
<thead>
<tr>
<th>Deformation Event</th>
<th>Structures/Indicators</th>
<th>Orientation and Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{n-1}</td>
<td>S_{n-2}</td>
<td>Earliest foliation observed rarely preserved in F_{n-1} isoclinal rootless folds.</td>
</tr>
<tr>
<td></td>
<td>S_{n-1}</td>
<td>Preserved in F_n folds with mm-scale spacing. Defined by aligned amphibole crystals. Original orientation undetermined but currently subparallel to S_n.</td>
</tr>
<tr>
<td></td>
<td>F_{n-1}</td>
<td>Isoclinal rootless cm- to m-scale folding subparallel to S_n. Original orientation undetermined (Fig. 2.7C).</td>
</tr>
<tr>
<td>D_n</td>
<td>L_s</td>
<td>Stretching lineation found rarely in host rocks defined by aligned biotite and amphibole crystals. Plunges ( \approx 20^\circ ) to the northeast (( \approx 045^\circ )). Difficult to find due to S_{n+1} overprint.</td>
</tr>
<tr>
<td></td>
<td>S_n</td>
<td>Dominant cm-scale foliation in the deposit defined by aligned biotite and amphibole crystals. Strikes between 40-55^\circ and has a near vertical dip (85-90^\circ) (Fig. 2.7B and C).</td>
</tr>
</tbody>
</table>
F<sub>n</sub> & Tight to isoclinal, cm- to m-scale asymmetric folds. Fold axis plunges between 10-40° to the northeast (Fig. 2.7C).

Sigma clasts & Quartz and plagioclase μm- to cm-scale sigma clasts seen in outcrop and thin section indicate a dextral shear sense of D<sub>n</sub>.

Delta clasts & Quartz and plagioclase μm- to cm-scale delta clasts seen in outcrop and thin section indicate a dextral shear sense of D<sub>n</sub>.

Mylonite & Mylonitic texture with mm-scale spacing parallel to S<sub>n</sub> containing delta and sigma clasts (plagioclase typically) indicating a dextral shear sense, and found in amphibole-plagioclase schist that is mineralogically equivalent to biotite-quartz schist (Fig. 2.7A).

S-C fabric & Found in biotite-quartz schist with a dextral shear sense; μm- to cm-scale.

D<sub>n+1</sub> & Late overprinting, generally cm-spaced foliation defined mainly by aligned amphibole crystals in chlorite-amphibole schist where it is displayed as crenulation cleavage. Strikes between 20 and 25° with a near vertical dip.

F<sub>n+1</sub> & Late open to tight folding with near vertical fold axes and axial planes locally responsible for change from S<sub>n</sub> to S<sub>n+1</sub>.

D<sub>n+2</sub> & Meter- to kilometer-scale faults that trend ≈ 10-15° north-northeast. Some suggestion of obliquity from geometry of nearby water bodies (Fig 2.7D).

Brittle fracturing & Late stockwork of fracture-filled veins containing chlorite and carbonate or quartz and amphibole generally subparallel to Ft<sub>n+2</sub> but penetrating along S<sub>n</sub> as well.

| Table 2.2. Summary of structural observations and measurement data (D = deformation, L = lineation, S = foliation, F = fold and Ft = fault). All data are presented with respect to n, which is the dominant structural event, relative to which all other events and structures are described within an individual sample or outcrop. |
Figure 2.8. Common structural elements observed in the MacLellan deposit and related Au-Ag occurrences. (A) Mylonitic texture parallel to $S_n$ in amphibole-plagioclase schist. (B) Crenulation cleavage in chlorite-amphibole schist showing $S_n$ and $S_{n+1}$. (C) $F_n$ folding in biotite-banded chlorite-amphibole schist. (D) $F_{n+2}$ faulting in outcrop showing dextral shear sense and crosscutting all lithologies.
Figure 2.9. Mylonitic textures seen at the Highway 391 outcrop. (A) Mylonitic texture parallel to $S_n$ in biotite-quartz schist. (B) Close up of (A) showing $S_n$ foliation and relict plagioclase phenocrysts in detail. (C) Side view looking southwest showing pockets of less altered and deformed amphibole-plagioclase schist and mylonitic textures and increased biotite content that this lithology displays with increased strain (the left of the photo).

**Alteration Styles and Occurrences**

Two major alteration events have been identified in the MacLellan deposit and related Au-Ag occurrences based on field and textural observations from outcrop and drill core, and from petrographic analysis of thin and thick sections.

*Biotite ± Quartz*

Biotite occurs only in areas exhibiting medium to high degrees of strain and the modal abundance of biotite increases with increased degree of strain. Unfoliated but variably deformed, μm- to mm-sized biotite crystals crosscut amphibole-plagioclase schist (Fig. 2.10A), have preferentially replaced foliated amphibole crystals in amphibole-plagioclase schist (Fig. 2.10B), and are a major constituent of
biotite-banded chlorite-amphibole schist and biotite-quartz schist (Figs. 2.5 and 2.6). Increased modal abundance of biotite is associated with the main ductile deformation event (D_n) (Table 2.3 and Fig. 2.8), as indicated by biotite development along S_n, which defines the predominant foliation in most localities. Biotite grains show no evidence of preferred alignment from other, earlier foliations and exhibit varying degrees of deformation that correspond to the development of S_{n+1} in D_{n+1} (Fig. 2.8B).

**Chlorite-Carbonate and Amphibole-Quartz**

Irregular, undeformed and unfoliated aggregates of chlorite crystals, which are 50 to 500 microns in diameter, and euhedral hornblende ± actinolite crystals, which are 0.1 to 1 centimeter, (Fig. 2.5D) replace to varying degrees the metamorphic minerals in all host rocks except granite and metagabbro. Chlorite and amphibole replace earlier, biotite that defines D_n and subhedral, foliated metamorphic amphibole crystals, and replacement chlorite and amphibole veins both crosscut and penetrate along the earlier S_n foliation in the affected host rocks (Fig. 2.9D and E). The chlorite and amphibole veins are associated with a relatively late, brittle deformation event (D_{n+2}) that is characterized by stockworks of carbonate, quartz, and carbonate-quartz veins and veinlets, which are associated with chlorite and amphibole veins, and have chlorite and amphibole selvages (Fig. 2.10D, E, and F). These veins and their associated alteration exhibit varying but typically relatively low degrees of localized deformation, ranging from undeformed to sheared, boudinaged, and dismembered. Chlorite-carbonate alteration is always present where amphibole-quartz alteration is present, however, chlorite-carbonate alteration also occurs on its own.
Figure 2.10. Hand specimen and outcrop photographs, and thin section photomicrographs showing examples of biotite and chlorite/amphibole alteration. (A) Drill core displaying secondary alteration biotite crosscutting metamorphic amphibole-plagioclase schist. (B) Photomicrograph of biotite-banded chlorite-amphibole schist oriented in thin section in plane-polarized light showing dominant biotite foliation (S_n). (C) Same sample as (B) under crossed polars showing relict plagioclase phenocrysts. (D) Outcrop photograph exhibiting relatively undeformed carbonate stockwork veins and chlorite alteration of amphibole-plagioclase schist. (E) Drill core showing chlorite veins crosscutting dominant biotite foliation (S_n) in biotite-quartz and quartz-biotite schist. (F) Photomicrograph in plane-polarized light of chlorite replacement after biotite in biotite-banded chlorite-amphibole schist.
Gold-Silver Mineralization and Sulphide Mineral Associations

Four different modes of occurrence of gold and silver were identified within the MacLellan deposit and associated Au-Ag occurrences and, based on field, textural, petrographic and geochemical observations, two stages of sulphide mineral and Au-Ag mineralization have been identified, each with distinct mineral occurrences and spatial distributions. The first occurrence of Au-Ag mineralization is associated with D_n ductile shearing and alteration, and comprises native gold grains, pyrrhotite, and pyrite. It is found in all Au-Ag occurrences in the study area and occurs associated with biotite alteration and lithologies containing biotite. The second occurrence of Au-Ag mineralization is associated with D_{n+2} brittle faulting, and comprises fracture-filling native gold, arsenopyrite, galena, and sphalerite. It is localized to fewer occurrences (Rushed Showing, Keewatin River, Main Zone and Nisku Deposit), where D_{n+2} brittle faults intersect D_2 ductile shear zones. Detailed descriptions of the individual Au-Ag and sulphide mineral occurrences are presented below.

Native Gold

Disseminated clusters of irregular gold grains, the grains ranging from 50 μm to 2 mm in size, occur parallel or sub-parallel to the dominant foliation defined by biotite (S_n)(Fig. 2.16), and as veinlets that fill late, brittle fractures within sulphide and silicate minerals (Fig. 2.11A). These grains and veinlets occur within biotite-quartz schist and biotite-banded chlorite-amphibole schist. Based on SEM-EDS data, these Au grains contain approximately 10 wt. % Ag.

Gold-Antimony Alloy

In places, gold-antimony alloy mantles the native gold grains described above and comprises approximately 50% Au and 50% Sb based on SEM-EDS analysis (Fig. 2.11B). This mineral is rare, has only been observed in biotite-quartz schist, and is generally associated only with relatively high Au assay values (≥ 3ppm Au).
**Silver in Galena**

Silver occurs within the structure of galena, based on the results of LA-ICP-MS analysis (Fig. 2.12A). Two distributions of Ag were observed within the same galena grains: 1) high Ag concentrations (500 to 2700 ppm) associated with low Fe concentrations (~ 50 ppm), and 2) low Ag concentrations (24 to 58 ppm) associated with high Fe concentrations (> 1000 ppm). The modal abundance of galena ranges from 1 to 20% within biotite-quartz schist, biotite-banded chlorite-amphibole schist and chlorite-amphibole schist, with higher abundances occurring in rocks containing greater proportions of biotite. The highest modal abundance of galena (~ 20% in core) occurs proximal to relatively late, north-northeast trending faults (e.g., Keewatin River, Nisku Deposit)

**Gold with Arsenopyrite**

Laser ablation ICP-MS analysis of arsenopyrite crystals shows that Au occurs as a substitution within the structure of arsenopyrite, and as coatings on grain surfaces and in microfractures within arsenopyrite (Figure 2.12B). Gold concentrations at the edges of arsenopyrite grains and adjacent to microfractures that cross arsenopyrite grains range from 43 to 118 ppm, whereas Au concentrations within arsenopyrite grains away from fractures and rims range from 0.8 to 3.8 ppm. If Au only occurred as a substitution in arsenopyrite (including the higher Au values from grain edges and microfractures), then whole-rock Au assay concentrations in As-rich samples could not be explained solely by these concentrations. If this were the case, only 10% of the Au found in the MacLellan deposit and related Au-Ag occurrences could be accounted for (Appendix II). Therefore, most of the gold in the MacLellan deposits must occur as native gold and alloys, such as Au-Sb.
Figure 2.11. Photomicrographs of Au-Ag occurrences. (A) Gold (≈ 90% Au, 10% Ag) under reflected light in late brittle veinlets associated with Gn, Sp, and Po within biotite-quartz schist. (B) SEM image of Au associated with Dₐ occurring as Au (≈ 90% Au, 10% Ag) and Au-Sb alloy (≈ 50% Au, 50% Sb) within biotite-quartz schist.
Figure 2.12. Photomicrographs of Au-Ag occurrences. (A) LA-ICP-MS spectra overlain on a reflected light photomicrograph of Gn showing Pb counts (red) and Ag counts (blue) over the length of a laser transect across Gn. Ag counts are relatively constant within Gn, indicating that the Ag is uniformly distributed within the structure of Gn. (B) LA-ICP-MS spectra overlain on a reflected light photomicrograph of Apy showing Fe counts (red) and Au counts (blue) over the length of a laser transect across Apy. Au counts are elevated within the Apy grain but spike at grain boundaries and along microfractures.
The mineralized zones of the MacLellan deposits are characterized by the presence of sulphide minerals, the most abundant of which are pyrite, pyrrhotite, chalcopyrite, arsenopyrite, galena, and sphalerite. These occur in biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist, but not in granite, metagabbro, and amphibole-plagioclase schist, and are associated with quartz veins and in the wall rock proximal to veins and alteration that are related to fluid infiltration events accompanying shearing (predominantly ductile).

Pyrrhotite and pyrite occur in all deposits in two different forms. Early pyrrhotite (Po₁) and pyrite (Py) are most abundant in the Main Zone and Nisku Deposit, where they occur as disseminations and stringers along the Sₙ foliation and have a modal abundance of about 20% of the rock in core samples. These minerals tend to be concentrated in biotite-rich portions of the rock. Although less abundant, both Po₁ and Py occur in all other zones along the Sₙ foliation, but are limited to 1 to 5% modal abundance, resulting in a more disseminated appearance. Irregular and fractured pyrrhotite (Po₁) grains are 25 microns to 1 millimeter in size and are oriented with Fₙ folding and Sₙ, much like magnetite and ilmenite, but without evidence of Fₙ₋₁ folding and grain alignment along Sₙ₋₁. Subhedral to anhedral pyrite grains range from 25 μm to 2 mm in size and display mutual grain boundary textures with arsenopyrite (Apy₁), irregular Au grains, biotite, and quartz (gold and pyrrhotite shown in, Fig. 2.13A). Pyrite grains show alignment along Sₙ and Fₙ folds, and pentlandite also occurs as fracture-related replacement in pyrrhotite (Po₁) (Fig. 2.13C). Late pyrrhotite (Po₂) shows no preferred alignment or evidence of orientation along Sₙ and occurs within all mineralized zones as disseminated grains that constitute 1 to 3% of core samples. In addition, Po₂ occurs as massive to semimassive aggregates comprising approximately 30 to 50% of the rock in areas where the various rock types are in contact with granite, both at surface and in core from drill holes located approximately 250 m south of the Rainbow Zone. Subhedral Po₂ grains are 25 μm to 2 mm in size and display mutual grain boundary textures with chalcopyrite (Ccp) and sphalerite (Sp), but also display replacement textures (i.e., caries texture) with these two sulphide minerals. The second occurrence of pyrrhotite (Po₂) has been replaced by chalcopyrite and both can be seen as
inclusions within sphalerite (Fig. 2.13B). Pyrrhotite (Po$_2$) grains show no preferred orientation, evidence of infilling in brittle ($D_{n+2}$) fractures in minerals, and rim replacement textures on arsenopyrite (Apy$_1$) (Fig. 2.13E) and fracture-related replacement textures in pyrite (Py) (Fig. 2.13F).

Two varieties of arsenopyrite (Apy$_1$ and Apy$_2$) have been identified, both of which occur primarily within biotite-quartz schist and biotite-banded chlorite-amphibole schist: 1) disseminated (Apy$_1$) grains that occur along the $S_n$ foliation with a modal abundance of approximately 1 to 3% in core, which are present in all mineralized zones and are concentrated along biotite-rich areas, and 2) disseminated (Apy$_2$) grains that show no preferred orientation with a foliation and occur in all mineralized zones, but have greater and more variable (2 to 20% in core) modal abundances than Apy$_1$. Grains of Apy$_1$ are subhedral to anhedral, 25 $\mu$m to 2 mm in size, and display mutual grain boundary textures with pyrite and irregular Au grains. Arsenopyrite$_2$ occurs in greatest modal abundance (10 to 20%) where $D_n$ ductile shears (striking 45 to 50°) and $D_{n+2}$ brittle faults (trending 10 to 15° north-northeast). These shear and fault intersections coincide with the Nisku Deposit, the Keewatin River near the Dot Zone, and the Rushed Showing outcrop (Fig. 2.3). Euhedral to subhedral and fractured Apy$_2$ grains, 100 $\mu$m to 2 mm in size, show mutual grain boundary textures with galena and fracture-related replacement textures in Po$_2$.

Chalcopyrite is rare (0.25 to 1% modal abundance) and only occurs where other sulphide minerals are present. Chalcopyrite grains are 25 $\mu$m to 2 mm in size and display mutual grain boundary textures with Po$_2$ and Sp but, as noted above, are also replaced by Po$_2$ in some samples.

Galena and sphalerite occur together and are present in greatest abundance at and proximal to intersections of $D_n$ ductile shearing (striking 45 to 50°) and $D_{n+2}$ brittle faulting (trending 10 to 15° north-northeast). Compared to Apy$_2$, however, galena (10 to 30% modal abundance in core) and sphalerite (5 to 10% modal abundance in core) grains show no evidence of brittle fractures. Sphalerite occurs as grains that are 25 $\mu$m to 2 mm in size and displays textures with Po$_2$ and Ccp as described above. Euhedral to subhedral galena grains are 100 $\mu$m to 2 mm in size,
exhibit mutual grain boundary textures with Apy$_2$ grains, and show fracture-related and rim replacement textures in Po$_2$, Ccp, and Sp (Fig. 2.13A and B). Micrometer-sized Au grains also occur in brittle fractures in minerals within biotite-quartz schist and biotite-banded chlorite-amphibole schist along with Gn and Apy$_2$ (Fig. 2.13D). The paragenesis of Au, and sulphide and oxide minerals is summarized in Figure 2.14.
Figure 2.13. Photomicrographs of various Au and sulphide mineral relationships under reflected light. (A) Au and Gn mineralization after Sp and Po. (B) Gn after Sp and Po (Sp and Po appear to be coeval). (C) Pn after Po. (D) Late Au filling fractures within biotite-quartz schist. (E) Po after Apy. (F) Sp, Po and Ccp after Py.

Figure 2.14. Paragenesis of gold, sulphide and oxide minerals.

**Gold-Silver Distribution**

The 3-dimensional spatial distributions of Au and Ag (as Au-equivalent) underlying the study area were modeled with GEMCOM™ software by Carlisle Goldfields Ltd. using fire assay concentration data obtained from drill core samples (Figure 2.15). The 2-dimensional spatial distribution of Au within the Crown Pillar outcrop area was contoured based on fire assay concentration data obtained from exploration trench samples (Figure 2.16). The Keewatin River and Main/Nisku Zones show more numerous and thicker zones of Au-Ag values, as well as increased abundance of Apy, Gn, and Sp.
Figure 2.15. 3-D image generated from Gemcom™ provided by Carlisle Goldfields Ltd. combined with approximate scale and landmark locations. Different colors represent different Au occurrence envelopes in which the minimum cut-off grade was 0.4 ppm Au. 2-D reference points (Dot Lake, Keewatin River and JR Lake) have been added solely for referencing purposes. The ‘Crown Pillar’ outcrop location within the map has been marked to associate with Figure 2.13.
Figure 2.16. Plan view map of the ‘Crown Pillar’ outcrop showing Au distributions based on Au assays from trench sampling that was conducted by Carlisle Goldfield Ltd. in 2008. The top left inset shows the lithologies of the outcrop.

Discussion

Host Rock Lithologies

Two prevailing opinions exist regarding the nature and origin of the host rocks to the MacLellan deposits and their potential association with Au-Ag occurrences. Fedikow (1986) indicates that the host rock sequence to the deposits contains Au- and Ag-bearing, syngeneric, exhalative rocks that provided primary metal enrichment, which was subsequently remobilized during deformation. Gagnon (1991) and Samson and Gagnon (1995) indicate that the Au-Ag deposits are associated with zones of high strain, quartz veins, and associated alteration (i.e., biotite) within a sequence of predominantly metavolcanic rocks. Thus, an important question is whether a relationship exists between particular lithologic units that is consistent with a syngeneric origin for the Au-Ag mineralization.
In this study, the predominant host rocks to the MacLellan deposits are described as comprising: 1) amphibole-plagioclase schist, 2) biotite-quartz schist, 3) biotite-banded chlorite-amphibole schist, 4) chlorite-amphibole schist, 5) granite, and 6) metagabbro. These rocks were previously characterized by Fedikow (1986) as: 1) aluminous fragmental basalt and mafic debris flows, 2) siliceous and biotite siltstone, 3) interlayered thinly bedded siltstone, basalt, and associated iron formation, and 4) high Mg-Ni-Cr basalt (picrite), basaltic tuff, and associated iron formation, and by Gagnon (1991) and Samson and Gagnon (1995) as: 1) plagioclase-hornblende schist, 2) biotite-plagioclase schist, 3) chlorite-quartz schist, and 4) chlorite-hornblende schist. The approximate lithologic equivalencies between the three studies are summarized in Table 2.3. Correlations between rock types are not exact due to differences in the scales of observation employed in the three studies, and a more detailed comparison of the rocks is presented below.

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<tr>
<td>Aluminous fragmental basalt and mafic debris flows</td>
<td>Plagioclase-hornblende schist</td>
<td>Amphibole-plagioclase schist</td>
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<tr>
<td>Siliceous and biotite siltstone</td>
<td>Biotite-plagioclase schist</td>
<td>Biotite-quartz schist</td>
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<tr>
<td>Interlayered thinly bedded siltstone, basalt and associated iron formation</td>
<td>Chlorite-quartz schist (intercalated with biotite-plagioclase schist)</td>
<td>Biotite-banded chlorite-amphibole Schist</td>
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<tr>
<td>Mg-Ni-Cr basalt, basaltic tuff (picrite) and associated iron formation</td>
<td>Chlorite-hornblende schist</td>
<td>Chlorite-amphibole schist</td>
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<tr>
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<td>Not Described</td>
<td>Metagabbro</td>
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<tr>
<td>Not Described</td>
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<td>Granite</td>
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Table 2.3. Comparison of observed lithologies between this study and that of Fedikow (1986) and Gagnon (1991); Samson and Gagnon (1995).
Lithologic Associations to Au-Ag Mineralization

Biotite-quartz schist and biotite-banded chlorite-amphibole schist described in this study occur throughout the MacLellan deposits. Fedikow (1986) identified a siliceous and biotite siltstone that was described as laminated to bedded, with both normal and reverse graded bedding, however, this rock type and these specific features were not observed in this study. The biotite-quartz schist and biotite-banded chlorite-amphibole schist that were observed exhibit mylonitic textures that could be interpreted as sedimentary bedding, however, these textures are always accompanied by secondary, replacement biotite and only occur in areas exhibiting the highest degree of strain. Grain fining toward areas of high strain was observed in deformed amphibole-plagioclase schist (Fig. 2.8A and 2.9), which was accompanied by secondary, replacement biotite that defines the S2 (see structural sequencing below) foliation. Secondary biotite crystals, and relict plagioclase phenocrysts that exhibit flattening and a dextral shear sense, indicate that biotite-quartz schist and biotite-banded chlorite-amphibole schist are not primary lithologies, but formed during D2 and retain some relict minerals and textures of the protolith (i.e., plagioclase phenocrysts) despite the majority of the rock now comprising metamorphic or post-metamorphic (i.e., alteration) minerals.

Furthermore, biotite was not observed outside areas of high strain (discussed below) and no evidence of structures indicative of a primary sedimentary unit (e.g., laminations or bedding) were observed. Biotite-quartz schist and biotite-banded chlorite-amphibole schist could be interpreted to be distinct lithologies that display a relationship to Au-Ag, but only insofar as the biotite that is associated with deformation and alteration, which dominates these units, is related to Au-Ag mineralization (below). Gradational contacts and textural indicators (e.g., grain fining with increased degree of strain, mylonitic textures, secondary biotite overprinting metamorphic minerals, relict and deformed plagioclase phenocrysts) indicate that biotite-quartz schist and biotite-banded chlorite-amphibole schist throughout the MacLellan deposits were produced by varying degrees of deformation and alteration of amphibole-plagioclase schist.

The descriptions of Mg-Ni-Cr basalt (picrite) of Fedikow (1986), the chlorite-
hornblende schist of Gagnon (1991) and Samson and Gagnon (1995), and the chlorite-amphibole schist in this study, are virtually identical. Identification of possible igneous protoliths and lithologic relationships between degree of strain and rock composition (e.g., the occurrence of high Mg basalts) are examined further using whole rock chemical mass balance in Chapter 3.

*Relationship of Au-Ag Mineralization to Alteration*

Secondary alteration in the study area is dominated by: 1) biotite ± quartz and 2) chlorite-carbonate ± amphibole-quartz. These two types of alteration are best represented by biotite alteration in amphibole-plagioclase schist (Fig. 2.10A) and chlorite-amphibole veins (Fig. 2.10D and E). All three studies (i.e., Fedikow, 1986; Samson and Gagnon, 1995; and this study) identified that Au-Ag mineralization is most closely associated with rocks containing the highest modal abundance of biotite (i.e., biotite-quartz schist), regardless of Au-Ag deposit. The major distinction between this study, in addition to having examined all of the MacLellan deposits, is that Fedikow (1986), which examined the East, Main and Rainbow Zones, identified the biotitic rocks to be sedimentary units (i.e., biotitic siltstones), and did not identify the secondary nature of the biotite, whereas Gagnon (1991), Samson and Gagnon (1995), which examined the Main Zone and Nisku Deposit, and this study identify biotite to be dominantly secondary in origin and the product of hydrothermal alteration accompanying ductile deformation. Although all of the studies identified Au-Ag mineralization as being associated with biotite, does a consistent relationship exist between a particular occurrence of biotite (i.e., a single lithology) and Au-Ag mineralization?

Biotite development along S$_2$ (see structural sequencing below) indicates that biotite crystallized in response to fluid-rock interaction during D$_2$ deformation. The D$_2$ deformation is constrained by the emplacement of the Burge Lake granodiorite at 1857 ± 2 Ma based on its emplacement prior to regional D$_2$ deformation (Beaumont-Smith et al., 2006). Given that granitoid-derived orthomagmatic fluids commonly cause potassic alteration, for example in most porphyry Cu-Mo systems (Strong, 1988; Robb, 2005), and that the Burge Lake granodiorite represents the minimum
age for D2 deformation (Beaumont-Smith et al., 2006), the latter is a possible source for the K-bearing fluid required to produce secondary biotite alteration and consequently Au-Ag mineralization. If this is the case, then spatial and temporal correlations should exist between emplacement of D2 synchronous granite/granodiorite intrusions and K metasomatism and Au-Ag mineralization elsewhere in the Lynn Lake greenstone belt.

Chlorite alteration is associated with stockworks of carbonate (± quartz) + chlorite (± amphibole) veins with chlorite ± amphibole alteration that both crosscut and penetrate the S2 foliation within the host rocks. These are similar to the quartz amphibole and carbonate ± quartz veins described by Gagnon (1991) and Samson and Gagnon (1995). The generally higher degree of strain exhibited by quartz + amphibole veins and associated amphibole alteration suggests that, although textural evidence indicates that alteration chlorite and amphibole are related spatially and temporally through D4 brittle strain, the amphibole-quartz alteration is slightly earlier and less common than the later chlorite-carbonate alteration. Chlorite-carbonate alteration affects all host rocks in the deposits except granite and metagabbro, and at least 80% of the host rocks contain varying amounts of crosscutting carbonate-quartz stockwork veins and associated chlorite-amphibole alteration, although to a lesser extent in biotite-quartz schist. This suggests that the earlier mylonitic textures associated with biotite alteration were less susceptible to subsequent chlorite-carbonate alteration. While rocks containing alteration chlorite only occur within areas of medium to high degrees of strain, individual chlorite crystals exhibit no evidence of significant deformation (e.g., foliation development, shearing, or folding) while metamorphic amphiboles within the same rock have preferred orientation (S2) suggesting that chlorite in the study area has a common origin, and is a product of relatively late fluid-rock interaction concurrent with D4 predominantly brittle deformation.

**Relationship of Au-Ag Mineralization to Deformation**

Fedikow (1986), Samson and Gagnon (1995), and this study all identified that Au-Ag mineralization is associated with rocks containing the greatest modal
abundances of biotite, however, is secondary biotite alteration structurally controlled?

*D_{1} Deformation*

The regional F_{1} folding that occurs in the study area is axial planar to the locally preserved S_{1} foliation, which is defined by amphibole crystals in biotite-banded chlorite-amphibole schist and chlorite-amphibole schist. S_{1} is preserved in F_{2} folds with millimeter-scale spacing. F_{1} is found as relict structures preserved within the S_{2} foliation, however, it is difficult to determine the original orientation of F_{1} due to it being isoclinal and rootless. S_{0} (primary layering) can be seen rarely in F_{1} folds subparallel to S_{1}, however, the rootless nature of F_{1} makes original orientation impossible to determine (Figure 2.8C). Park et al. (2002) suggested that because the S_{0-1} enveloping surface is approximately 20° to the horizontal and there is a low angle of intersection between S_{0} and S_{1}, that F_{1} folds were isoclinal and had shallow-dipping axial planes prior to D_{2}. Evidence observed in outcrops and samples in this study are consistent with the assessment of Park et al. (2002).

*D_{2} Deformation*

D_{2} structures are dominant in the study area and Au-Ag mineralization occurs in association with structures formed during this deformation event (discussed below). The centimeter-scale spaced S_{2} foliation in the study area is defined by biotite and amphibole grains and occurs in most lithologies, except for granite and gabbro. The S_{2} foliation strikes between 40 and 55° and has a near vertical dip (85 to 90°). The F_{2} folds are asymmetric and those measured in the study area have fold axes that plunge between 10 and 40°, which is consistent with observations made by Park et al. (2002). A dextral shear sense on S_{2} is exhibited by S-C fabrics, small F_{2} folds, delta clasts, and sigma clasts exposed in outcrop. Rare instances of an L^{s} stretching lineation, which is defined by biotite and amphibole grains and plunges approximately 20° to the northeast, indicates a slight obliquity to the dextral shear sense. Mylonitic textures associated with D_{2} deformation are exhibited in places in outcrops throughout the study area and are manifested by
grain-size reduction of clasts and rock fragments, which is symmetrical about areas of increased strain (i.e., cores of mylonitic zones).

**D₃ Deformation**

These relatively late structures obscure earlier structures in many of the outcrops in the study area and give rise to difficulties in identifying L₂ stretching lineations. The F₃ folds are open to tight and have near vertical axes and axial planes. These features were also observed by Park et al. (2002), however, they were grouped into D₄ due to an inferred regional event that was not identified in either this study or the study of Park et al. (2002). For this reason, this inferred event (previously D₃) is excluded from the interpretation of structural features presented in this study. Evidence of S₃ includes a crenulation cleavage that is defined by amphibole crystals in chlorite-amphibole schist. This foliation strikes between 20 and 25°, has a near vertical dip, and locally overprints and forms an approximately 20° angle with S₂ (Fig. 2.8B).

**D₄ Deformation**

This event, which is characterized by predominantly brittle deformation, produced stockworks of veins and crosscutting faults that trend approximately 10 to 15° north-northeast and can be seen in places in outcrop, as well as regionally on aerial photographs (Fig 2.8D). The surface exposure of fault planes typically cannot be seen in outcrop, however, the sense of movement along the faults can be interpreted from dextral offsets of correlated lithologic units, structures, or veins and associated alteration between adjacent outcrops. In addition, the distribution and asymmetric shapes of many lakes and rivers (e.g., Keewatin River-Eldon Fault) in aerial photographs may also suggest a downward component of fault movement due to the commonly sharp eastern edges and irregular western edges of water bodies, which suggest an oblique movement downward to the north-northeast. If there were an upward sense of movement along with dextral offsetting of the faults, the eastern edges of water bodies would display sharp edges. Gold-silver concentrations are highest and occur over longer intervals in areas where D₂ ductile
shear zones and associated earlier Au-Ag-quartz-biotite mineralization is cut by and/or reactivated by these later D₄ brittle faults. An example of this reactivation would be the ‘North shear’ discussed by Gagnon (1991) which has late chlorite alteration in the selvages of these reactivated 045° striking D₂ shears. Structural evidence and interpretations presented above show similarities to observations made previously by Park et al. (2002), however, major differences between the studies include the nature of the lithologies, due to Park et al. (2002) using primarily Fedikow (1986; 1991) lithologies, and the absence of a D₃ regional deformation event.

The critical relationships between lithology, deformation, and alteration that have been identified in this study are: 1) biotite in biotite-quartz schist and biotite-banded chlorite-amphibole schist developed during ductile D₂ deformation based on biotite defining the major S₂ foliation in the study area and D₂ ductile kinematic indicators having been observed within these lithologies and alteration, and 2) chlorite-carbonate ± amphibole-quartz alteration, which occurs in biotite-banded chlorite-amphibole schist and chlorite amphibole schist, is related to the predominately brittle D₄ deformation event based on the occurrence of veins of chlorite-carbonate and amphibole-quartz that cross-cut and penetrate D₂ and D₃ structures, and pervasive chlorite alteration related to stockwork carbonate veins and brittle northeast trending faults that replaced earlier biotite alteration.

*Au-Ag Mineralization and Sulphide Mineral Associations*

The MacLellan Au-Ag deposit has been described as primarily syngenetic in origin with secondary remobilization (Fedikow, 1986) or as epigenetic in origin and associated with quartz + sulphide veins and biotite alteration hosted within high strain zones (Gagnon, 1991). The model of Fedikow (1986) requires that an Au- and Ag-bearing primary exhalative metasedimentary unit be present, whereas the model of Gagnon (1991) requires that Au-Ag mineralization be associated with veins, high strain zones, and alteration.

The observations presented in this study, which include textural and field relationships obtained from outcrop and drill core samples, Au-Ag assay data,
mineral chemistry, and lithogeochemistry (Appendix IV, SEM-EDS and LA-ICP-MS), indicate that Au-Ag mineralization occurs primarily within ductile shear zones (i.e., mylonites) within amphibole-plagioclase schist that are host to alteration zones characterized by partial to complete replacement of primary and metamorphic minerals by biotite ± quartz. Figure 2.17 shows the timing of Au and sulphide mineral emplacement in the study area.

![Figure 2.17: Paragenesis of gold, sulphide minerals and oxide minerals. Deformation events have been added to illustrate the relative timing of mineral deposition.](image)

The association between Au-Ag mineralization, deformation, and alteration indicates that: 1) a mineralizing event that included Au and Au-Sb alloys, which occur within D₂ fabrics, occurred during D₂, 2) a mineralizing event that is characterized by Au within microfractures and within the structure of arsenopyrite (Apy₂), which occurs proximal to intersections between northeast trending D₄ brittle faults and D₂ ductile shear zones, occurred during D₄. Silver within galena, which is found proximal to northeast trending D₄ brittle faults and D₂ ductile shear
intersections, also indicates a mineralizing event during \(D_4\). Arsenopyrite (Apy\(_2\)), galena and sphalerite, which show fracture-related textures and spatial proximity to \(D_4\) brittle faults and \(D_2\) ductile shear intersections, indicates that these minerals precipitated as part of the same mineralizing event.

These observations indicate that Au-Ag mineralization in the study area initially comprised predominantly grains of Au and Au-Sb alloy, which were deposited by a potassic fluid that produced biotite ± quartz alteration during \(D_2\) ductile deformation in rocks proximal to the zones of highest strain. No correlation was observed between a particular primary lithology and Au-Ag mineralization (cf. Fedikow, 1986). The Burge Lake granodiorite represents the minimum age for \(D_2\) deformation based on the interpretations of Beaumont-Smith et al. (2006), and could also be the source of the K- and SiO\(_2\)-bearing fluid that would be required for quartz veins, biotite ± quartz alteration, and potentially Au-Ag mineralization. The earlier Au-Ag mineralizing event was followed by a later fluid-infiltration event that accompanied the \(D_4\) deformation, which was dominated by brittle conditions, and deposited Au- and Ag-bearing sulphide minerals (e.g., arsenopyrite and galena, respectively) and Au as mantles on and in microfractures within previously formed sulphide and silicate minerals. The thickening of Au-rich zones and the increased frequency of their occurrence proximal to points of intersection between brittle \(D_4\) north-northeast-trending faults and ductile \(D_2\) (strike \(\approx 45^\circ\)) shear zones supports the interpretation of a second Au-Ag bearing fluid and demonstrates that Au- and Ag-depositing fluids penetrated, to some extent, the previous \(D_2\) structural architecture. It is possible that Au-Ag mineralization associated with \(D_2\) was remobilized during \(D_4\), however, this seems unlikely due to the increase in Au-Ag grades as well as the addition of other elements to the system that were unrelated to the earlier mineralization (e.g., As, Pb, Zn in arsenopyrite, galena, and sphalerite) at locations proximal to \(D_2\) ductile shear and \(D_4\) fault intersections.

**Further Considerations**

Based on this study, Au-Ag mineralization in the MacLellan deposit and related Au-Ag occurrences is the result of hydrothermal fluid infiltration along zones
of high strain that formed during two separate events (D₂ and D₄). Replacement and relict mineral textures and crosscutting relationships indicate that the mineralization was accompanied by emplacement of quartz veins and biotite ± quartz alteration of amphibole-plagioclase schist. The deformation and alteration produced secondary rock types (biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist). Examination of the lithogeochemistry of the protoliths and their altered equivalents (e.g., high field strength element concentrations, mass balance analyses) is required to identify the igneous protoliths and to quantify mass changes accompanying deformation and alteration. Mineral textures described in this study indicate that mineralogic changes accompanying deformation and alteration also include replacement of metamorphic minerals by hydrothermal chlorite and amphibole during D₄ brittle deformation. Characterization of mineralogic and whole rock compositional change accompanying deformation and biotite, chlorite, and amphibole alteration is critical to determining their association with and role in Au-Ag mineralization, if any, and their potential use as exploration vectors elsewhere in the Lynn Lake greenstone belt. These issues shall be explored further in Chapter 3.

References


Beaumont-Smith, C.J. and Rogge, D.M., 1999. Preliminary structural analysis and gold metallogeny of the Johnson Shear Zone, Lynn Lake greenstone belt (parts of


Fedikow, M.A.F., Baldwin, D.A. and Taylor, C., 1986. Gold mineralization associated with the Agassiz metatotect and the Johnson Shear Zone, Lynn Lake greenstone belt,


Chapter 3 – Lithogeochemical changes accompanying deformation and mineralization in the MacLellan deposit and related Au-Ag occurrences, Lynn Lake, Manitoba: implications for element mobility and deposit genesis.

Introduction

The MacLellan Au-Ag deposit is located approximately 7 km northeast of the town of Lynn Lake, Manitoba (Fig. 3.1). The MacLellan deposit and associated Au-Ag occurrences (the K, Dot, Rainbow, West, Main, and East Zones, and Nisku Deposit), hereafter referred to as the MacLellan deposits, comprise a significant Au-Ag ‘camp’ situated within the northern portion of the Lynn Lake greenstone belt (LLGB) that is currently estimated to contain just over 2 million ounces of Au equivalent (NI 43-101 report; Ewert et al., 2012). The lithologic units and styles of deformation and alteration are generally consistent across all of the deposits with the main difference being the presence or absence of intersecting D₂ ductile and D₄ brittle shear zones that are accompanied, in places, by increases in modal abundances of sulphide minerals and Au-Ag grades (Chapter 2)(Figs. 3.2 and 3.4).

Although the major metamorphic rock types and the styles of mineralization in the MacLellan deposits have been characterized based on their field occurrences, mineral assemblages, and textural relationships (Chapter 2), identification of the igneous or sedimentary protoliths, whether an association exists between a particular protolith and Au-Ag mineralization, and quantitative determination of chemical changes accompanying deformation and Au-Ag mineralization remain uncharacterized. Protoliths cannot be identified based solely on field occurrences and metamorphic mineral assemblages, therefore, geochemical analyses are required. Protolith identification is critical to interpreting the geologic setting and petrogenesis of the LLGB, as well as providing the geochemical information required to conduct regional lithologic correlations and to quantify compositional changes
accompanying deformation, alteration, or Au-Ag mineralization. In this chapter, the following questions will be explored:

1. The metamorphic host rocks to the MacLellan deposits have been identified as amphibole-plagioclase schist, biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist (Chapter 2). What were the igneous or sedimentary protoliths to these metamorphic lithologies?

2. Au-Ag mineralization within the MacLellan deposit has been interpreted to be either predominantly syngenetic with remobilization during subsequent deformation (Fedikow, 1986) or epigenetic and associated with zones of high strain, quartz veins, and potassic alteration (Samson & Gagnon, 1995; Chapter 2). Is Au-Ag mineralization in the study area associated with: 1) a specific, primary, Au- and Ag-bearing lithologic unit (i.e., is syngenetic), 2) high strain zones, veins, and associated hydrothermal alteration (i.e., is epigenetic), or 3) a specific, primary lithologic unit that has been subsequently deformed and altered (i.e., is syngenetic with subsequent remobilization)?

3. Textural similarities among, and gradational contacts between, the various lithologic units comprising the host rocks to the MacLellan deposit suggest that some of the metamorphic host rocks may share a common protolith, and that mineralogic and compositional variations are the result of later alteration and deformation events (Chapter 2). Is there a lithology from which the various host rocks in the study area could have been derived through varying degrees of deformation and alteration?

Chapter 3 presents the results of lithogeochemical analyses conducted on the least altered and deformed host rocks to the mineralization, and their altered and deformed equivalents, and interprets these data in the context of the field, mineralogic, textural, and assay data presented in Chapter 2.


Background

Lithologies

Fedikow and Gale (1982) and Fedikow (1986) interpreted the host rocks to the MacLellan Au-Ag mineralization to be metamorphosed, fine-grained, tuffaceous, clastic (siltstones), and chemical (iron formation) sedimentary rocks, interbedded with variably altered metabasalts (high Mg-Ni-Cr basaltic flows or picrites), all of which have been altered to varying degrees by biotization, silicification, carbonatization, and chloritization. Gagnon (1991) and Samson and Gagnon (1995) identified three amphibolite grade metamorphic lithologies (chlorite-hornblende schist, biotite-plagioclase schist, and chlorite-quartz schist) as dominating the MacLellan deposit host rocks. Chlorite-hornblende schist is equivalent to rocks described by Fedikow (1986) as picrites, and biotite-plagioclase schist is equivalent to rocks previously considered to be metasediments and altered, porphyritic metabasalts. The chlorite-quartz schist was considered by Gagnon (1991) and Samson and Gagnon (1995) to be the product of relatively late, hydrothermal alteration of biotite-plagioclase schist and the picritic rocks described by Fedikow (1986).

Based on the results of this study (Chapter 2), the host rocks to mineralization at the MacLellan deposit and related Au-Ag occurrences are dominated by: 1) amphibole-plagioclase schist, 2) chlorite-amphibole schist, 3) biotite-banded chlorite-amphibole schist, and 4) biotite-quartz schist (quartz-biotite schist). Field, textural, and structural observations indicate that the biotite-quartz schist and chlorite-amphibole-schist are variably altered and deformed equivalents of amphibole-plagioclase schist (Table 3.1). These rocks occur as stratiform units with thicknesses ranging from 1 to 500 m and strike lengths ranging from 100 m to 3 km. The metamorphosed, altered, and deformed nature of the rocks, however, makes determination of the protoliths impossible without using lithogeochemistry.
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Aluminous fragmental basalt and mafic debris flows</td>
<td>Plagioclase-hornblende schist</td>
<td>Amphibole-plagioclase schist</td>
</tr>
<tr>
<td>Siliceous and biotite siltstone</td>
<td>Biotite-plagioclase schist</td>
<td>Biotite-quartz schist</td>
</tr>
<tr>
<td>Interlayered thinly bedded siltstone, basalt and associated iron formation</td>
<td>Chlorite-quartz schist (intercalated with biotite-plagioclase schist)</td>
<td>Biotite-banded chlorite-amphibole schist</td>
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<tr>
<td>Mg-Ni-Cr basalt, basaltic tuff (picrite) and associated iron formation</td>
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<td>Chlorite-amphibole schist</td>
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</table>

Table 3.1. Comparison of lithologies between this study and those of Fedikow (1986), Gagnon (1991), and Samson and Gagnon (1995).

Mineralization

Gold mineralization at the MacLellan deposit has been described as being either syngenetic in origin, hosted by primary exhalative sedimentary units, and has undergone metamorphism and remobilization (Fedikow and Gale, 1982; Fedikow, 1986) or as epigenetic in origin and associated with zones of high strain, quartz-sulphide mineral veins, and associated hydrothermal (predominantly biotite) alteration that occurred synchronous with and after peak metamorphism (Gagnon, 1991; Samson and Gagnon, 1995; Chapter 2). These models are, however, based largely on the Main Zone of the MacLellan Au-Ag deposit and do not take into account host rocks, deformation, alteration, and Au-Ag mineralization across all of the mineralized zones (i.e., K, Dot, Rainbow, West, Main, and East zones and the Nisku deposit)(Fig. 3.2). Confirmation of the presence of primary, Au- and Ag-bearing sedimentary units within the host rock sequence is essential to determining the role, if any, of sedimentary-exhalative processes in the formation of the MacLellan deposits. Gagnon (1991) and Samson and Gagnon (1995) did not identify a primary sedimentary unit in the Main Zone that was host to syngenetic Au-Ag mineralization as previously interpreted by Fedikow (1986). Fedikow (1992)
performed a lithogeochemical comparison to determine if what were interpreted to be metasedimentary rocks were actually highly altered metabasalts, however, the results of this investigation were inconclusive (i.e., ‘metasedimentary’ and metabasaltic rocks units were found to have similar compositions).

In general, deformation and alteration styles were consistent among all of the MacLellan deposits (Chapter 2). The host rocks to the deposits have been affected by four deformation events (D1 through D4) (Chapter 2). Two of the events (D2 and D4) are associated with two different episodes of hydrothermal fluid infiltration during which Au-Ag mineralization occurred. The two major alteration types observed in the study area are: 1) biotite ± quartz, and 2) chlorite-carbonate/amphibole-quartz. Gold-silver mineralization is most closely associated with biotite alteration, as evidenced by the occurrence of high Au and Ag grades within the two rocks bearing secondary, replacement (i.e., alteration) biotite (i.e., biotite-quartz schist and biotite-banded chlorite-amphibole schist). Biotite ± quartz alteration occurred associated with D2 ductile deformation, and chlorite-carbonate/amphibole-quartz alteration occurred during D4 predominately brittle deformation based on cross-cutting relationships. The latter alteration event is not directly associated with Au-Ag enrichment. The proximal, syn-D2 Burge Lake granite/granodiorite, which may occur in the host rock sequence as minor granitic intrusives, is a potential source of the Au- and Ag-bearing potassic fluid responsible for biotite-quartz alteration.

Gold and silver are most closely associated with biotite-banded chlorite-amphibole schist and biotite-quartz schist and occur as: 1) native Au grains (~ 90% Au and 10% Ag), 2) grains of Au-Sb alloy (~ 50% Au and 50% Sb), 3) Au within, on the surface of, and in microfractures within arsenopyrite, and 4) Ag within galena. Native Au grains and veinlets that occur within other minerals account for greater than 90% of the Au and galena accounts for the majority of the Ag within the MacLellan deposits. The Nisku Deposit, and the Main and Dot Zones (Fig. 3.2) contain the highest concentrations of Au and Ag and are characterized by increased modal abundances of arsenopyrite, galena, and sphalerite relative to other occurrences. These deposits occur at the intersection between D4 north-northeast
brittle faults and D₂ northeast ductile shear zones. These intersections likely represent the most important structural feature when prospecting for potential high-grade Au-Ag mineralization in the study area.

Figure 3.1. Regional geology map showing Lynn Lake and the MacLellan Au-Ag deposit (modified from Beaumont-Smith et al., 2006).

Figure 3.2. Map of the MacLellan deposit and related Au-Ag occurrences showing previous occurrence nomenclature.
Methodology

All properties located northeast of the town of Lynn Lake, Manitoba that are controlled by Carlisle Goldfields Ltd. and where Au and Ag occurrences have been previously documented (i.e. the K, Dot, Rainbow, West, Main, and East Zones, and Nisku Deposit) were included in this study (Fig. 3.2). The study area was large enough to enable comparison with studies previously conducted on various aspects of the Au-Ag mineralization in the area (e.g., Augsten, 1985; Fedikow, 1986; Gagnon, 1991; Fedikow, 1992; Samson and Gagnon, 1995; Park et al., 2002) as well as studies that addressed the regional geology and metallogeny of the Lynn Lake greenstone belt (e.g., Milligan, 1960; Koo, 1976; Gilbert et al., 1980; Beaumont-Smith and Böhm, 2002; Beaumont-Smith et al., 2006).

Drill Core and Outcrop Description and Sampling

The majority of the 1268 rock samples used in this study were collected from drill core during logging activities associated with exploration programs performed by Carlisle Goldfields Ltd. during 2008 on properties containing the MacLellan deposits. Two hundred and six of the rock samples that were obtained from outcrops and drill core and described in Chapter 2 were also used to characterize chemical changes associated with alteration and deformation. Of these 206 samples, 22 oriented samples were obtained from 6 of 12 outcrops that are located within the study area, and an additional 3 outcrops located east of and outside the study area (Fig. 3.3). The outcrops were mapped at a scale of 1:50, and detailed lithologic, textural, and structural data were obtained. The remaining 1062 samples were provided by Carlisle Goldfields Ltd. from core collected from 4 representative holes drilled in 2008 (MG07-01, MG07-02, MG07-03, and MG07-04) (Fig. 3.3). These 4 drill holes are considered representative because they cross all host rock types and display the full range of alteration, deformation, and mineralization observed in the study area. Most samples were obtained from drill core because of extensive surface weathering and the general lack of outcrop in the study area.

Prior to sample collection, core from each of the drill holes used in this study was re-logged to ensure consistency in the descriptions across the sampling
locations. The drill core was characterized for lithology, structure and deformation (e.g., presence of foliation, lineation, shear zones, and folds), alteration (e.g., cross-cutting mineral textures) and mineralization (e.g., presence of veins and sulphide minerals). Where possible, orientation data (e.g., strike and dip, trend and plunge) were also obtained from the drill core.

Representative outcrop and drill core samples of least altered and deformed rocks and altered and deformed equivalents were collected. Samples were obtained from the various lithologic units, styles of deformation, and examples of Au-Ag and base metal sulphide mineral occurrences (i.e., veins and associated alteration). Additional details pertaining to core logging and sample collection are provided in Chapter 2.
Figure 3.3. Map of the MacLellan deposit and related Au-Ag occurrences showing drill hole and outcrop locations.

Petrographic Analysis

The 86 polished thin and 91 polished thick sections that were used in Chapter 2 were also used in this investigation. The sections were examined to identify metamorphic, alteration, and sulphide mineral assemblages based on equilibrium textures, relative timing of crystallization based on cross-cutting and replacement textures, and relative timing of deformation events based on microstructural analysis and cross cutting relationships. Thick and thin sections were photographed and their mineralogy and textures were determined using an Olympus® BX51 polarizing transmitted and reflected light petrographic microscope. In some cases, mineral identification was aided with compositional information.
obtained using an FEI Quanta® 200f field emission scanning electron microscope (SEM) coupled with EDAX® energy dispersive spectroscopy (EDS). Details of the samples and thin sections and analytical instrumentation operating conditions are provided in Appendix II and IV respectively.

Five samples from alteration assemblages were prepared and analyzed for chlorite and amphibole mineral classification purposes using a Rigaku® MiniFlex™ powder X-ray diffractometer (XRD) and Crystal Impact Match!® software (Appendix IV).

**Whole-rock Chemical Analysis**

Fifty samples, representing least altered and deformed rocks, and their altered and deformed equivalents, were selected for whole rock geochemical analysis. The analyses were performed by ACTLabs in Ancaster, Ontario and included major element oxides (SiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, CaO, Na₂O, K₂O, TiO₂, and P₂O₅) and minor and trace elements (Sc, Be, V, Cr, Co, Ni, Cu, Zn, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, In, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Tl, Pb, Bi, Th, and U) using lithium metaborate/tetraborate fusion followed by digestion and analysis using inductively coupled plasma mass spectrometry (ICP-MS). The samples submitted for chemical analysis were taken as approximately 50 g sub-samples from drill core that ranged from 0.3 and 1.0 m in length.

Data for an additional 1062 whole rock geochemical analyses were provided by Carlisle Goldfields Ltd. for core samples obtained from 4 representative holes that were drilled in 2008 (MG07-01 to MG07-04). The analyses were performed to quantify compositional change accompanying Au and Ag mineralization-related deformation and alteration. The analyses were performed by TSL Laboratories in Saskatoon, Saskatchewan and included quantification of Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Sn, Sr, Ti, V, W, Y, Zn, and Zr abundances using inductively coupled plasma atomic emission spectroscopy (ICP-AES). The samples were obtained as approximately 50 g sub-samples from drill core that
ranged from 0.3 and 1.0 m in length. The results of the whole rock ICP-MS and ICP-AES analyses are provided in Appendix III.

**Chlorite and Amphibole Elemental Microanalysis**

Eleven thick sections prepared from rocks interpreted to be representative alteration assemblages containing chlorite and amphibole were selected for analysis using laser ablation (LA)-ICP-MS at the Great Lakes Institute for Environmental Research (GLIER) at the University of Windsor, Ontario. The LA-ICP-MS analysis was conducted to determine the trace element content of chlorite and amphibole minerals within these types of alteration. Forty, individual chlorite and amphibole LA-ICP-MS microanalyses were performed. Operating conditions of the laser and mass spectrometer and results of the LA-ICP-MS analyses are provided in Appendix IV.

**Protolith Identification and Mass Balance Analysis**

Fifty whole rock lithogeochemical analyses were used in conjunction with a spreadsheet-based computer program (EASYGRESGRANT; López-Moro, 2012) to quantify volume and mass balance compositional changes accompanying deformation and alteration. EASYGRESGRANT generates isocon diagrams, which are used to quantify mass or volume change using a graphical approach derived from Gresens (1967) and Grant (1986; 2005). The program does not require arbitrary scaling of elemental concentration data that has been used to fit a wide range of concentrations onto a single figure, which can introduce errors, and selection of apparently immobile elements is verified through a least squares linear regression method. The program can be used as an independent method of validating mineralogical and textural evidence accompanying rock deformation and alteration.
Figure 3.4 Geological map of the MacLellan Au-Ag deposit and related occurrences showing lithologic units.
Results

Geochemical Comparison of Rock Types

The host rocks to the MacLellan deposits have been previously classified using metamorphic nomenclature based on field, textural, and petrographic analysis (Chapter 2). The following is a presentation of major element oxide (Table 3.1) and rare earth element (REE) concentration data, which were used to characterize and compare the various lithologies and their altered and deformed equivalents (Figs. 3.5 to 3.10). The geochemical data are presented in their entirety in Appendix III and IV.

Amphibole-plagioclase schist (Fig. 3.5A) has the lowest high field strength element (HFSE) abundances of all of the rocks investigated and displays a relatively flat chondrite-normalized REE signature with a small positive Eu anomaly. Concentrations of Zr in this rock type range from 22 to 29 ppm, Nb from 1.3 to 1.8 ppm, Hf from 0.6 to 0.8 ppm, and Ta from 0.07 to 0.14 ppm. Biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist exhibit chondrite-normalized patterns with varying degrees of light relative to heavy REE enrichment (Fig. 3.8). Chlorite-amphibole schist is characterized by higher MgO, Ni, and Cr abundances with respect to biotite-quartz and biotite-banded chlorite-amphibole schists. Concentrations of MgO range from 5.79 to 19.77 wt. %, Ni from 40 to 710 ppm, and Cr from 90 to 1760 ppm in samples of these rock types (Table 3.2, Appendix III). Chlorite-amphibole schists also have the lowest chondrite-normalized light relative to heavy REE enrichments (Fig. 3.6B). Biotite-quartz schist is characterized by higher concentrations of K₂O (2.66 to 3.57 wt. %) and Rb (58 to 104 ppm), relative to the other rock types (Table 3.2, Appendix III), and has the highest chondrite-normalized light relative to heavy REE enrichment (Fig. 3.5B). Samples of biotite-banded chlorite-amphibole schist exhibited major element oxide abundances (Table 3.2, Appendix III) and chondrite-normalized light relative to heavy REE enrichments that are intermediate between chlorite-amphibole and biotite-quartz schists (Fig 3.6A).
Five samples exhibited chondrite-normalized REE patterns that differ from the samples that they have been classified with using field, textural, and petrographic methods. The chondrite-normalized patterns have been displayed in Figure 3.7 to contrast the differences with their apparent equivalents in Figures 3.5 and 3.6. Figure 3.8 is a plot of La/Lu versus Eu/Eu* showing differences between representative rock types at the MacLellan deposit. As with Figure 3.7 this plot shows that the same 5 samples though characterized with their apparent equivalents (discussed above) plot away from their lithologic groupings determined through field, textural and petrographic methods. The significance of these rocks is discussed below.
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<th>Rock Type</th>
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<th>Fe₂O₃T (%)</th>
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<th>CaO (%)</th>
<th>Na₂O (%)</th>
<th>K₂O (%)</th>
<th>TiO₂ (%)</th>
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<tr>
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<td>9.42</td>
<td>0.15</td>
<td>4.81</td>
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<td>0.59</td>
<td>1.16</td>
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Table 3.2. Rock types at the Maclellan deposit showing major oxides and loss on ignition average values for each rock type.
Figure 3.5. Chondrite-normalized REE (rare earth element) plot. Chondrite values are after Sun and McDonough (1995) of predominant host rock types at the MacLellan Au-Ag deposit and related occurrences: A) amphibole-plagioclase schist, B) biotite-quartz schist, C) biotite-banded chlorite-amphibole schist, D) chlorite-amphibole schist, and E) anomalous rock compositions.
Figure 3.6. Chondrite-normalized REE (rare earth element) plot. Chondrite values are after Sun and McDonough (1995) used in confirming lithological groupings at the MacLellan Au-Ag deposit and related occurrences. (A) Biotite-banded chlorite-amphibole schist. (B) Chlorite-amphibole schist.
Figure 3.7. Chondrite-normalized REE (rare earth element) plot. Chondrite values are after Sun and McDonough (1995) used in confirming lithological groupings at the MacLellan Au-Ag deposit and related occurrences. Rock types seen here have different REE patterns from the rocks they have been classified with based on field, textural, and petrographic analyses.
Figure 3.8. La/Lu vs. Eu/Eu* displaying rock types seen at the MacLellan deposit
**Compositional Change Accompanying Chlorite-carbonate and Amphibole-quartz Alteration**

Rocks exhibiting evidence of chlorite-carbonate and amphibole-quartz alteration (e.g. chlorite-amphibole schist, but also within all rock type to some extent) correlate with high Mg, Ni, and Cr concentrations, regardless of rock type, based on geochemistry provided by Carlisle Goldfields Ltd. (intervals within drill holes MG07-01 to MG07-04, Appendix III). The chlorite-carbonate alteration is clearly defined by crosscutting and replacement textures, and shows no sign of deformation while metamorphic amphiboles within the chlorite-amphibole schists and biotite-banded chlorite amphibole schists have preferred orientation along S₂ (Fig. 3.9E and F). Figure 3.10 is a plot of drill hole MG07-02 comparing rock types with Ni and Cr abundances. Higher Cr and Ni concentrations (> 200 ppm) correlate with the occurrence of chlorite-carbonate veins in drill core. Laser ablation ICP-MS and SEM-EDS analyses show that Cr concentrations in amphibole and chlorite (from various rock types) range from 2 to 5330 ppm and 22 to 6579 ppm, respectively, and Ni concentrations range from 23 to 285 ppm and 45 to 740 ppm, respectively (Fig. 3.11, App. IV). The LA-ICP-MS spectra show uniform distributions and relatively high concentrations of Ni and Cr across the aggregates of alteration chlorite crystals, and higher abundances of Ni and Cr also occur where alteration chlorite crystals are in contact with, and have partially replaced biotite and amphibole. SEM-EDS analyses show similar results to the LA-ICP-MS analyses and indicate that alteration chlorite has relatively high Mg concentrations ranging from 12.45 to 16.79 wt. % Mg (Fig. 3.11B, App. IV). Chlorite associated with chlorite-carbonate alteration has been determined to be chromium clinochlore based on XRD analysis (Appendix IV).
Figure 3.9. Representative alteration styles observed at the MacLellan deposit and related Au-Ag occurrences: A) amphibole-plagioclase schist showing relict plagioclase phenocrysts, B) amphibole-plagioclase schist showing biotite alteration, C) amphibole-plagioclase schist showing chlorite alteration, D) amphibole-plagioclase schist partially replaced by biotite, which exhibits a mylonitic texture, E) amphibole-plagioclase schist partially replaced by cross-cutting chlorite-carbonate veins and F) secondary biotite in biotite-quartz schist being crosscut by a chlorite vein.
Figure 3.10. Down hole plot of drill hole MG07-02 showing Ni and Cr variation with changing rock type. Where Ni and Cr show high levels coincides with chlorite-carbonate veins which crosscut all previous lithologies. Inset picture shows an example of this.
Figure 3.11. LA-ICP-MS spectra overlain on thick section showing Cr in chlorite minerals with laser transects: A) sample 118228 showing Al (red) and Cr (blue) counts across alteration chlorite crystal aggregates (2596.50 ppm Cr), and B) sample 118253 showing Cr counts across alteration chlorite crystal aggregates and biotite, which has been replaced by chlorite (5551.41 ppm Cr).
Discussion

Protoliths and Alteration

The host rocks to the MacLellan deposit were previously characterized by Fedikow (1986) as: 1) aluminous fragmental basalt and mafic debris flows, 2) siliceous, biotite siltstone, 3) interlayered thinly bedded siltstone, basalt, and associated iron formation, and 4) Mg-Ni-Cr basalt, basaltic tuff (picrite), and associated iron formation. Samson & Gagnon (1995) characterized the host rocks to the Main Zone of the MacLellan deposit as: 1) plagioclase hornblende schist, 2) biotite-plagioclase schist, 3) chlorite-quartz schist, and 4) chlorite-hornblende schist. The interpreted equivalencies between the host rocks identified in this study and those of Fedikow (1986) and Samson and Gagnon (1995) are provided in Table 3.3. The correlations between rock types are not exact due to differences in the scales of observation between the studies (i.e., this study included all of the MacLellan deposits, whereas previous studies addressed only some of the occurrences).

<table>
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<td>Aluminous fragmental basalt and mafic debris flows</td>
<td>Plagioclase-hornblende schist</td>
<td>Amphibole-plagioclase schist</td>
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<td>Biotite-plagioclase schist</td>
<td>Biotite-quartz schist</td>
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<tr>
<td>Interlayered thinly bedded siltstone, basalt and associated iron formation</td>
<td>Chlorite-quartz schist (intercalated with biotite-plagioclase schist)</td>
<td>Biotite-banded chlorite-amphibole schist</td>
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<tr>
<td>Mg-Ni-Cr basalt, basaltic tuff (picrite) and associated iron formation</td>
<td>Chlorite-hornblende schist</td>
<td>Chlorite-amphibole schist</td>
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<td>Granite</td>
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</table>

Table 3.3. Comparison of lithologies between this study and those of Fedikow (1986), Gagnon (1991), and Samson and Gagnon (1995).
Of the rock types identified within the MacLellan deposits, only amphibole-plagioclase schist exhibits relict igneous textures (i.e., phenocrysts) and all other rock types occur only in areas characterized by deformation and hydrothermal alteration (e.g., biotite, chlorite and amphibole replacement). Contacts between all rock types are gradational and field and textural relationships suggest that the various host rocks may have had a common protolith. Relict plagioclase phenocrysts, which are relatively undeformed and unaltered in amphibole-plagioclase schist, occur in all other rock types and exhibit varying degrees of strain depending on the rock type (Fig. 3.12). Relict phenocrysts are least deformed in amphibole-plagioclase schist and most deformed in biotite-quartz schist.

Of the host rock types identified in the MacLellan deposits, only amphibole-plagioclase schist exhibits little to no biotite and chlorite alteration and, based on the results of whole rock analyses, has loss on ignition (LOI) values less than 1.5% (Appendix III). Biotite and chlorite alteration (meter-scale in core and outcrop), relatively high LOI values (greater than 3%), the presence of carbonate and quartz veins, and indicators of relatively high degrees of strain (e.g., C-S fabrics, sigma and delta clasts, shear bands) indicate that the remaining rock types (biotite-quartz schist, biotite-banded chlorite-amphibole schist, or chlorite-amphibole schist) appear to be the product of progressive deformation and alteration of amphibole-plagioclase schist. Evidence of unaltered and undeformed examples of these rock types could not be found outside areas exhibiting high degrees of strain. When least altered and deformed samples of amphibole-plagioclase schist are plotted on igneous rock classification diagrams, they plot in the tholeiitic (Fig 3.13A) or subalkaline (Fig. 3.13B) basalt fields.
Figure 3.12. Representative rock types observed at the MacLellan deposit and related Au-Ag occurrences showing common textural elements: A) amphibole-plagioclase schist, B) biotite-quartz schist, C) biotite-banded chlorite-amphibole schist, and D) chlorite-amphibole schist.
Figure 3.13. Magma series classification plots for amphibole-plagioclase schist: A) SiO$_2$ vs. Fe$_2$O$_3$/MgO (modified after Miyashiro, 1974), and B) Nb/Y vs. Zr/Ti (modified after Winchester and Floyd, 1977).

Biotite-quartz and biotite-banded chlorite-amphibole schists, which were previously interpreted to be siliceous, biotite siltstones by Fedikow (1986), were not observed to exhibit evidence of normal and reverse graded bedding. These rocks,
which represent variably altered and deformed equivalents of amphibole-plagioclase schist, exhibit progressive grain size reduction that is symmetrical about areas exhibiting high degrees of strain resulting from progressive mylonitization that developed during D2. Biotite does not occur outside areas of high strain and is interpreted to be an alteration that formed from fluid-rock interaction during D2 deformation, which has been linked to the emplacement of the Burge Lake granite/granodiorite by Beaumont-Smith et al. (2006) (Chapter 2). Biotite is secondary, replaces metamorphic ferromagnesian minerals (e.g., amphibole), and there is no evidence of unaltered and undeformed versions of biotite-quartz schist and biotite-banded chlorite-amphibole schist.

This study has also not found any evidence of banded iron formation within the host rock sequence to the MacLellan deposits. Rock comprising bands of biotite and sulphide minerals (principally pyrite and pyrrhotite) with and without quartz, which represents mineralized, deformed, and altered amphibole-plagioclase schist, was observed. The banded nature of the rock is the result of deformation and alteration and does not reflect primary layering.

Rocks identified in this study as amphibole-plagioclase schist (and its deformed and altered equivalents) were previously classified as Mg-Ni-Cr basalts or picrites (Fedikow 1986, 1991). Classification of a volcanic rock as a picrite requires that the rock contain olivine (Kerr and Arndt, 2001). In the case of the MacLellan deposit host rocks, primary magmatic mineralogy and textures have been replaced by metamorphic equivalents. Therefore, classification of the rocks requires use of whole rock geochemistry. Rocks containing relatively elevated abundances of Mg, Ni, and Cr also exhibit relatively high LOI values (greater than 2 % and averaging 5 %) and high degrees of strain. Rocks exhibiting Mg abundances in the range of picritic rocks (MgO between 11 and 18%) appear to show evidence of addition of Mg, Ni, and Cr during hydrothermal alteration and replacement by chlorite and amphibole (see discussion below). Consequently, reliable classification of the host rocks as picrites using either igneous mineralogy and textures or geochemistry is impossible.
A relationship between Cr-clinochlore-carbonate alteration and relatively high Mg, Ni and Cr concentrations has been observed within the deposit (Fig 3.10), suggesting that Mg, Ni and Cr concentrations were elevated during late hydrothermal alteration. Secondary pentlandite has also been seen observed as late fracture filling within pyrrhotite (Chapter 2, Fig. 2.12C), providing additional evidence for late hydrothermal mobility of Ni with the MacLellan deposit host rocks. The association of relatively high Mg, Ni and Cr concentrations with late, secondary chlorite alteration and sulphide (pentlandite) mineralization are inconsistent with these rocks representing an igneous protolith of picritic composition. Therefore, what were characterized as picrites by Fedikow (1986; 1991) are interpreted in this study to be chlorite-amphibole schists with high but variable Mg, Ni and Cr values that are primarily the alteration products of amphibole-plagioclase schist. High Mg (MgO > 12 wt. %), Ni and Cr concentrations have also been observed in biotite-quartz schist and biotite-banded chlorite-amphibole schist where secondary Cr-clinochlore-carbonate alteration occurs.

The Cr-clinochlore analyzed using LA-ICP-MS contains on average 13.68 wt. % Mg. Rocks exhibiting significant modal abundances (> 70%) of Cr-clinochlore and evidence of potential volume loss (see below) associated with D2 deformation would contain concentrations of MgO in the range of picrites. Fedikow (1986) suggested the chlorite-rich groundmass in these rocks to be the metamorphosed equivalent of a secondary mineral assemblage after olivine (Fox and Johnson, 1981). Alteration Cr-clinochlore, unlike other minerals within the same rocks (hornblende ± actinolite), is unfoliated and post-dates the regional deformation that affected the entire study area as well as the syn-D2 potassic alteration event associated with Au-Ag mineralization.

Field relationships, petrography, and mineral and whole rock chemistry indicate that the host rock sequence to the MacLellan deposit and related Au-Ag occurrences was originally dominated by a single, porphyritic metabasalt protolith (amphibole-plagioclase schist) with a tholeiitic basalt composition prior to deformation and alteration. Because amphibole-plagioclase schist represents the least altered rock within the host rock sequence, its composition can be used as a
baseline to test a model in which this unit was altered to: 1) biotite-quartz and biotite-banded chlorite-amphibole schists during a syn-D$_2$ biotite ± quartz hydrothermal alteration event, and 2) high Mg-Ni-Cr chlorite-amphibole schist during a syn-D$_4$ chlorite-carbonate (± amphibole-quartz) hydrothermal alteration event.

If amphibole-plagioclase schist is the precursor to the other host rocks to the MacLellan deposits then: 1) there should be evidence of this rock type outside areas of high strain and hydrothermal alteration, 2) there should be evidence of field and textural relationships showing systematic transition between the various rock types, and 3) mass balance analysis using amphibole-plagioclase schist as a protolith should show volume and compositional changes consistent with field and petrographic evidence of alteration and deformation observed in the study area.

Apart from granite, amphibole-plagioclase schist is the only rock type that occurs outside of areas of high strain and hydrothermal alteration (Fig. 3.4). It is also the least deformed of the host rocks in the study area and it is the only rock that preserves igneous textures (i.e., it is porphyritic). Figures 3.9 and 3.12 show textural similarities between the various rock types and field relations that suggest that biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist have been derived from amphibole-plagioclase schist.

Grant (1986; 2005), adapting a method originally developed by Gresens (1967), used isocons to quantify mass and volume changes accompanying rock deformation and alteration. This method was subsequently adapted by López-Moro (2012) into a spreadsheet-based software (EASYGRESGRANT). The model tested in this case is that the amphibole-plagioclase schist was the single protolith from which all other rock types were derived. Amphibole-plagioclase schist was input as the unaltered rock and each of the other rock types (biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist) were input as the altered equivalents. It was assumed that the heavy REE were immobile and the isocon line was defined by these heavy REE common to all rock types. Volume loss was calculated using a line defined by the elemental data and rock densities.
(calculated from representative samples of each rock type) and compared to the isocon line.

Based on field and textural relationships, deformation, and alteration, the rocks in the areas of highest strain (biotite-quartz schist) should show the highest amount of volume loss due to $D_2$ shearing and mylonitization elongating and compressing grains and reducing the permeability and porosity of the rocks (Chapter 2). The rocks showing the least amount of strain with the most pervasive Cr-clinochlore alteration should also show volume loss, but to a far lesser extent due to their distal relationship to $D_2$ shears, coupled by potential volume gain associated with $D_4$ brittle chlorite-carbonate veins. In this case, biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist show a loss of volume consistent with a high to low degree of mylonitization from proximal to distal from shearing of the amphibole-plagioclase schist (Figs. 3.14 to 3.17). Biotite schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist show volume losses of 72 %, 46 %, and 24 (coarse-grained) to 33 % (fine-grained), respectively, which is consistent with expectations based on field and textural relationships. In order for the amphibole-plagioclase schist to be altered to biotite-quartz schist, a source of K (e.g., the Burge Lake granite/granodiorite?) is required in order to produce biotite alteration and because the rocks also exhibit mylonitic textures, they should also undergo a deformation-related volume reduction. There is a gain of $K_2O$ and Rb consistent with biotite alteration occurring from fluids associated with the Burge Lake granite/granodiorite and $D_2$ ductile shearing (3.14B). In order for amphibole-plagioclase schist to be altered to chlorite-amphibole schist, Mg, Ni and Cr would have to be added to the rocks. Furthermore, because the alteration accompanies either carbonate/quartz veins or syn-$D_4$ shearing, rock volume could increase (i.e., veins) or decrease (i.e., shearing). Figure 3.16B and 3.17B indicate that Mg, Ni and Cr were added to amphibole-plagioclase schist coupled with volume loss in order to produce chlorite-amphibole schist. Because biotite-banded chlorite-amphibole schist gradational between biotite-quartz and chlorite-amphibole schists, a range of mass gain or loss would be expected for these rock types, and Figure 3.17B shows this to be the case.
Figure 3.14.Isocon and histogram plots showing volume change and elemental gain/loss in rock types. In the case of Isocon plots (A) the red line represents the isocon line using the heavy rare earth elements as immobile elements within the rocks. This red line compared to the purple constant volume line indicates the volume change experienced by the altered rock compared to the protolith. Red lines that plot above the purple constant volume line indicate volume loss, and red lines that plot below the purple constant volume line indicate volume gain. (A) Biotite-quartz schist (altered) compared to amphibole-plagioclase schist (unaltered). (B) Elemental gain/loss of amphibole-plagioclase schist due to alteration into biotite-quartz schist.
Figure 3.15. Isocon and histogram plots showing volume change and elemental gain/loss in rock types. In the case of Isocon plots (A) the red line represents the isocon line using the heavy rare earth elements as immobile elements within the rocks. This red line compared to the purple constant volume line indicates the volume change experienced by the altered rock compared to the protolith. Red lines that plot above the purple constant volume line indicate volume loss, and red lines that plot below the purple constant volume line indicate volume gain. (A) Biotite-banded chlorite-amphibole schist (altered) compared to amphibole-plagioclase schist (unaltered). (B) Elemental gain/loss of amphibole-plagioclase schist due to alteration into biotite-banded chlorite-amphibole schist.
Figure 3.16. Isocon and histogram plots showing volume change and elemental gain/loss in rock types. In the case of Isocon plots (A and B) the red line represents the isocon line using the heavy rare earth elements as immobile elements within the rocks. This red line compared to the purple constant volume line indicates the volume change experienced by the altered rock compared to the protolith. Red lines that plot above the purple constant volume line indicate volume loss, and red lines that plot below the purple constant volume line indicate volume gain. (A) Fine-grained chlorite-amphibole schist (altered) compared to amphibole-plagioclase schist (unaltered). (B) Elemental gain/loss of amphibole-plagioclase schist due to alteration into fine-grained chlorite-amphibole schist.
Figure 3.17. Isocon and histogram plots showing volume change and elemental gain/loss in rock types. In the case of Isocon plots (A and B) the red line represents the isocon line using the heavy rare earth elements as immobile elements within the rocks. This red line compared to the purple constant volume line indicates the volume change experienced by the altered rock compared to the protolith. Red lines that plot above the purple constant volume line indicate volume loss, and red lines that plot below the purple constant volume line indicate volume gain. (A) Coarse-grained chlorite-amphibole schist (altered) compared to amphibole-plagioclase schist (unaltered). (B) Elemental gain/loss of amphibole-plagioclase schist due to alteration into coarse-grained chlorite-amphibole schist.
Differences between the flat chondrite-normalized REE patterns of rock types showing anomalous compositions (Fig. 3.7) and the light REE-enriched chondrite-normalized patterns of the other rock types (Fig. 3.5, and 3.6) are the result of compositional changes associated with Cr-clinochlore alteration. The rock samples with flat chondrite-normalized REE patterns do not exhibit petrographic evidence of chlorite alteration, whereas all others rock samples show varying amounts of chlorite alteration. The REE patterns shown in Figure 3.7 can be explained through derivation of these rocks from amphibole-plagioclase schist (Fig. 3.5A) by volume loss and preferential removal of plagioclase, as evidenced by the negative Eu anomalies. The compositions of the other host rocks shown in Figures 3.5B, and 3.6A and B can be explained by derivation from amphibole-plagioclase schist through volume loss and enrichment of LREE most likely as a result of hydrothermal chlorite alteration.

Using field relationships and textures, petrography and mass balance analysis, the only precursor protolith is the amphibole-plagioclase schist and all of the other lithologies are the result of varying degrees of deformation and alteration of this rock type, which agrees with Gagnon (1991), Samson and Gagnon (1995), and Chapter 2. Furthermore, Au-Ag mineralization occurred during D₂ and D₄ deformation and no evidence of a syngenetic, Au- and Ag-bearing primary exhalative unit, as suggested by Fedikow (1986), was observed. Amphibole-plagioclase schist exhibits textures, field relations, and geochemistry consistent with a continental or rift related, tholeiitic basalt, because textures and structures indicative of a subaqueous eruptive environment (e.g., pillows) have not been observed.

References


Chapter 4 - Conclusions

Based on data collected and interpretations made in response to the questions posed during preparation of this thesis, the following conclusions can be made:

*Do the MacLellan Deposit and related Au-Ag occurrences have similar host rock lithologies, mineralization styles, alteration types, and structure?*

This study has shown that the MacLellan Deposit and related Au-Ag occurrences can be interpreted on a scale that allows correlation between lithology, alteration type, structure, and mineralized zones. All zones and occurrences within the study area contain similar lithologies and alteration styles (Fig. 2.4). The Nisku Deposit, and Main and Dot Zones (Fig. 2.2) contain the most abundant occurrences of Au-Ag mineralization and have increased modal abundances of Apy, Gn and Sp relative to the other zones. These deposits occur at the intersection between D4 north-northeast striking brittle fault zones and D2 ≈ 045° striking ductile shear zones, and the most significant differences in mineralization styles present in individual occurrences is the presence or absence of these intersecting D2 and D4 structures.

*What are the host rocks to the MacLellan Deposit and related Au-Ag occurrences, and is there a relationship between a particular lithologic unit or units and Au-Ag mineralization?*

The host rocks to mineralization at the MacLellan Deposit and related Au-Ag occurrences are: 1) amphibole-plagioclase schist, 2) chlorite-amphibole schist, 3) biotite-banded chlorite-amphibole schist, and 4) biotite-quartz/quartz-biotite schist, 5) metagabbro, and 6) granite. Au-Ag is most closely associated with the biotite-banded chlorite-amphibole schist and biotite-quartz/quartz-biotite schist. Field, textural, and structural observations indicate that the biotite-quartz schist and
chlorite-amphibole-schist are the variably altered and deformed equivalents of amphibole-plagioclase schist.

*Are the mineralization styles present in the MacLellan Deposit and related Au-Ag occurrences related to particular deformation events and structures and, if so, what is the relationship?*

Four deformation events (D₁ through D₄) have affected the host rocks to the MacLellan Deposit and related Au-Ag occurrences. Two of the events (D₂ and D₄) are associated with two different hydrothermal fluid infiltration events during which Au-Ag mineralization occurred. The intersections of D₄ north-northeast striking brittle fault zones and D₂ ≈ 045° striking ductile shear zones contain the greatest modal abundances of Au, Ag (within Au and Gn), Ap, Gn, and Sp, and the highest concentrations of Au and Ag. These intersections likely represent the most important structural feature when prospecting for potential high-grade Au-Ag mineralization.

*What are the mineralization styles and associated alteration types present within the MacLellan Deposit and related Au-Ag occurrences, and is there a relationship between a particular alteration type and Au-Ag mineralization?*

In general, alteration styles were consistent among all of the occurrences. The two major alteration types observed in the study area are: 1) biotite ± quartz ± sulphide minerals, and 2) chlorite + carbonate ± hornblende + quartz. Au and Ag are most closely associated with biotite alteration, as evidenced by the occurrence of high Au and Ag grades within the two rocks bearing secondary, replacement (i.e., alteration) biotite (biotite-quartz schist and biotite-banded chlorite-amphibole schist). Biotite ± quartz ± sulphide mineral alteration occurred earlier based on its relationship with D₂ ductile deformation and chlorite + carbonate ± amphibole + quartz alteration occurred later based on its crosscutting relationship with D₂ structures and its association with D₄ predominately brittle deformation. This later alteration event is not directly associated with Au and Ag enrichments. The syn-D₂ Burge Lake granite/granodiorite, which may be present in the host rock sequence as
minor granitic intrusives, is a potential source of Au- and Ag-bearing potassic fluid responsible for biotite-quartz alteration in the MacLellan Deposit.

Gold and silver occur in 4 modes: 1) native Au grains (≈ 90% Au and 10% Ag), 2) grains of Au-Sb alloy (≈ 50% Au and 50% Sb), 3) Au within, on the surface of, and in microfractures in arsenopyrite, and 4) Ag within galena. Native Au grains and Au veinlets within other minerals account for greater than 90% of the Au within the deposits and galena accounts for the majority of the Ag within the deposits.

What were the igneous or sedimentary protoliths to what are now the metamorphic host rocks to the MacLellan Deposit and related Au-Ag occurrences?

Based on field, petrographic and lithogeochemical evidence, there is one precursor to the various lithologies that occur in the MacLellan Deposit and related Au-Ag occurrences: amphibole-plagioclase schist, which was formerly a porphyritic basalt. The other lithologies are the product of varying degrees of deformation and hydrothermal alteration accompanying two major structural events: D2 and D4. There is no evidence of primary siltstones, sedimentary structures, banded iron formation, pillow structures, or an unaltered picrite as described by Fedikow (1986; 1991) in the various Au-Ag occurrences. Field, textural, and geochemical data indicate that Mg, Ni, and Cr concentrations have been elevated in lithologies that underwent chloritization resulting from hydrothermal alteration accompanying D4 deformation.

The Cr-clinochlore + carbonate (± amphibole + quartz) hydrothermal alteration, rather than a primary volcanic unit (i.e., ‘picrite’), explains the elevated concentrations of Mg, Ni and Cr within the deposit, however, this relatively late alteration event is not associated with Au-Ag mineralization. As previously stated, intersecting D2 and D4 structures, combined with biotite ± quartz ± sulphide mineral alteration control Au-Ag mineralization within the occurrences (Chapter 2), and provide the exploration vectors for similar Au-Ag mineralization within the district.
**Is the MacLellan Au-Ag Deposit epigenetic or syngenetic in origin with respect to Au-Ag mineralization?**

Gold and silver are controlled by fluid events associated with $D_2$ and $D_4$ deformation and the intersecting architecture that they create (Chapter 2). This study has shown that Au-Ag are not associated with a specific primary Au- and Ag-bearing lithologic unit, or Au and Ag that have been remobilized from a specific primary Au-Ag-bearing lithologic unit as a result of deformation. Field and textural relationships and lithogeochemistry indicate that a metabasalt (i.e., amphibole-plagioclase schist), which did not contain anomalously high, primary Au-Ag concentrations, was variably deformed and altered into the host rocks presently seen at the MacLellan Deposit and related Au-Ag occurrences (biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist) and that Au-Ag was primarily introduced during a ductile deformation event ($D_2$) that was accompanied by biotite ± quartz ± sulphide mineral alteration (cf. Gagnon, 1991; Samson and Gagnon, 1995).

**Further Considerations**

Based on this study, all zones and occurrences within the study area contain similar lithologies and alteration styles. The Nisku deposit, Main and Dot zones contain the most abundant occurrences of Au-Ag mineralization and have increased amounts of Apy, Gn and Sp relative to other zones. These deposits occur at the intersection between $D_4$ north-northeast brittle faults and $D_2 \approx 45^\circ$ ductile shear zones and the most significant differences in the styles of mineralization that are present in individual zones within the study area are the presence or absence of these intersecting $D_2$ and $D_4$ structures. Gold and silver mineralization in the MacLellan deposit is the result of hydrothermal fluid infiltration along zones of high strain that formed during two separate events ($D_2$ and $D_4$). Replacement and relict mineral textures and crosscutting relationships indicate that the mineralization was accompanied by emplacement of quartz veins and biotite ± quartz alteration of amphibole-plagioclase schist. Amphibole-plagioclase schist has been altered by
biotite ± quartz alteration (D_2) and chromium clinochlore ± carbonate alteration (D_4). The deformation and alteration produced secondary rock types (biotite-quartz schist, biotite-banded chlorite-amphibole schist, and chlorite-amphibole schist) that are genetically related to the amphibole-plagioclase schist. Further research into the origin of the biotite ± quartz alteration and chromium clinochlore ± carbonate alteration would be beneficial due to the unknown source for the Mg-Ni-Cr bearing fluid. This may have implications for the providence of ‘altered picrite’ that has been found in other greenstone belts and the tectonic history of many regions worldwide. Very little is currently understood about Ni and Cr mobility in hydrothermal systems, and as such, studying this phenomenon may change the way we characterize and interpret lithologies and protoliths in areas of high strain and alteration zones.
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