STRUCTURAL RELATIONS BETWEEN THE POLYDEFORMED
FLIN FLON ARC ASSEMBLAGE AND MISSI GROUP SEDIMENTARY ROCKS,
FLIN FLON AREA,
MANITOBA AND SASKATCHEWAN

by

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the degree of Master of Science

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Frontispiece: A view towards the southeast of the community of Flin Flon, the North and South Main shafts, and the open pit. The 260 metre tall stack is provided for scale.

Abstract

The structure of the Flin Flon area (Manitoba and Saskatchewan), host to the Flin Flon and Callinan Cu-Zn orebodies, has been examined through mapping of mesoscopic and macroscopic structures in both the ca. 1900 Ma Flin Flon arc assemblage volcanic basement and the unconformably overlying ca. 1845 Ma Missi Group continental sedimentary cover sequence. The volcanogenic massive sulphide orebodies occur within the basalt-dominated basement stratigraphy in close proximity to the unconformity. The unconformity cuts through a significant thickness of basement section and is markedly angular, suggesting that the basement was deformed prior to erosion and sedimentation, consistent with regional constraints. A generation of early folds identified only within the volcanic basement provides evidence for early deformation.

The cover sequence, composed of fluvial sandstones interspersed with conglomeratic units, records three principal fold- and foliation-forming events. The extent, character and variability of these structures were documented during this study. All deformation observed within the cover sequence is correlative with deformation observed within the volcanic basement. Significant low-angle overlap of basement on cover is attributed to development of a D_1 north-verging nappe and subsequent thrust displacement on the overturned basement-cover contact. Data from diamond-drill holes which intersect this basement-cover contact at depth constrain a minimum displacement for the D_1 thrust. This local early north-verging deformation provides evidence for a period of northward vergence that preceded a regional event which is marked by southwestward thrusting at peak metamorphic conditions across the Flin Flon Belt. D_2 deformation produced closed to tight, west-verging overturned folds with a well-developed axial planar cleavage and a pervasive stretching lineation. As a result of F_1 - F_2 folding, the Missi Group rocks within the field area demonstrate type I - type II interference patterns. D_3 deformation generated open folds of the S_2 and a weakly to moderately developed spaced axial planar S_3 cleavage. Associated D_3 high-strain zones dissect the basement-cover sequence and have variable displacement. D_3 - D_4 deformation produced sinistral-oblique, brittle-ductile reverse faults that offset all older features.

The contact between the Flin Flon arc assemblage and the Missi Group was investigated in detail during this study. In the southern part of the study area, this contact is defined by an unconformity, while in the northern part of the study area it is mainly defined by a thrust fault developed on the overturned limb of an F_1 fold.

The correlation of structural features across the D_4 Ross Lake fault was completed by constructing a fault plane map. Based on this construction, the location of the F_1 Flin Flon Creek syncline in the hanging-wall of the D_4 fault was reinterpreted and the Club Lake structure and Little Cliff Lake fault were proven to be a continuous D_1 thrust fault.

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Table of Contents

Frontispiece.	i
Abstract.	ii
Acknowledgements.	iii
Table of Contents.	iv
List of Tables.	vi
List of Figures.	vii
List of Plates.	viii
 Chapter 1 : Introduction.	 1
1.1 - Introduction.	1
1.2 - Location, access and physiography.	3
1.3 - Previous Work.	5
1.4 - Present Study	7
1.5 - Outline of thesis	8
 Chapter 2 : General Geology.	 10
2.1 - Regional Geology.	10
2.2 - Local Geology.	15
2.2.1 - Flin Flon arc assemblage.	15
2.2.2 - Missi Group.	22
2.2.3 - Boundary Intrusions.	23
2.3 - Local structural geology.	25
2.4 - Metamorphism.	30
 Chapter 3 : Structural Geology.	 32
3.1 - Introduction.	32
3.2 - Structures in the southern region.	32
3.2.1 - Missi Outlier.	34
3.2.2 - Ross Creek syncline.	37
3.2.3 - Mud Lake syncline.	39
3.2.4 - Relationships at the basement-cover contact.. .	45
3.2.5 - Burley Lake syncline.	46
3.2.6 - Sepple Hill shear zone.	48
3.2.7 - Microscopic relationships.	53
3.3 Structures in the northern region.	54
3.3.1 - Pipeline fold interference basin.	55
3.3.1.1 - D ₂ deformation.	55
3.3.1.2 - D ₁ deformation.	59
3.3.1.3 - D ₃ deformation.	60

3.3.1.4 - Summary.	61
3.3.2 - Flin Flon Creek syncline.	63
3.3.3 - Microscopic relationships in Missi Group	64
3.3.4 - Hidden Lake synform.	66
3.3.5 - Relations between the basement-cover contact and the Club Lake structure	69
3.3.5.1 - Western section of Club Lake structure.	70
3.3.5.2 - Summary.	73
3.3.5.3 - Eastern section of Club Lake structure.	73
3.3.5.4 - Summary.	82
3.3.6 - Railway faults.	85
3.3.7 - Area north of Ross Lake.	93
3.3.8 - Microscopic relationships within the Flin Flon arc assemblage.	99
3.4 - Brittle-ductile fault structures.	103
3.5 - Summary of structural geology.	109
Chapter 4 : Discussion.	114
4.1 - Deformational summary.	114
4.1.1 - Pre-Missi Group deformation	114
4.1.2 - D ₁ deformation.	115
4.1.3 - D ₂ deformation.	120
4.1.4 - D ₃ and D ₄ deformation.	123
4.2 - Regional tectonic setting.	124
4.3 - Relationships of surface mapping to Callinan mine geology.	128
4.4 - Advances made in this study.	132
4.5 - Conclusions.	134
4.6 - Recommendations for further study	137
References.	139
Vita.	145

List of Tables

Table 1. Summary of deformational models from the Flin Flon Area. . . .	26
Table 2. Summary of deformational events.	125

List of Figures

Chapter 1

Figure 1.1	Location of study area.	2
------------	---------------------------------	---

Chapter 2

Figure 2.1	Map of Trans-Hudson Orogen.	11
Figure 2.2	Map of Flin Flon Belt showing tectono-stratigraphic assemblages.	12
Figure 2.3	Geology of the Flin Flon area.	17
Figure 2.4	Stratigraphy of the study area.	18
Figure 2.5	Structural geology of study area; previous interpretations.	28

Chapter 3

Figure 3.1	Structural geology of study area; interpretations from this study.	33
Figure 3.2	Geology of the Missi Outlier.	35
Figure 3.3	Equal area stereonet plots showing S_0 data and S_2 cleavage traces.	38
Figure 3.4	Equal area stereonet plots showing S_2 and L_2 data, and S_2 cleavage traces.	41
Figure 3.5	Equal area stereonet plots showing S_3 data and S_3 cleavage traces	43
Figure 3.6	Map of Sepple Hill area.	49
Figure 3.7	Map of Pipeline interference basin with S_0 data, stereonet and two cross-sections.	56
Figure 3.8	Three dimensional view of the Pipeline interference basin	62
Figure 3.9	Map view and two cross-sections from eastern Club Lake structure.. . . .	75
Figure 3.10	Drill hole data from Hidden Lake synform incorporated into three cross-sections.	83
Figure 3.11	Three dimensional view of the Club Lake structure.	84
Figure 3.12	Structural relationships north of Ross Lake.	95
Figure 3.13	Fault plane map of the Ross Lake fault.	105

Chapter 4

Figure 4.1	Four cross-sections from study area	Inside back cover
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Map 1	Northern study area.	Inside back cover
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Map 2	Southern study area.	Inside back cover
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◆ Chapter 1 - INTRODUCTION ◆

1.1 - Introduction

The area surrounding the town of Flin Flon, Manitoba is underlain principally by two suites of rocks (Fig. 1.1). The first is a package of juvenile island-arc tholeiitic volcanic rocks (Flin Flon arc assemblage) which host the Flin Flon and Callinan Cu-Zn massive sulphide deposits (Bailes and Syme, 1989; Syme and Bailes, 1993). The second suite unconformably overlies these volcanic rocks, and consists of conglomerates and sandstones (Missi Group), deposited in a continental fluvial sedimentary environment (Fig. 1.1; Ambrose, 1936a; Stauffer, 1990; and references therein). Deformation that occurred during the Trans-Hudson orogeny (Hoffman, 1988; Gordon et al., 1990; Lucas et al., 1996) produced multiple generations of folds and foliations that are preserved in rocks of both suites. The contact between the two rock suites is of particular interest because of the variation it exhibits throughout the study area (Ambrose, 1936a; Stockwell, 1960). In one portion of the field area, the contact is a well-preserved unconformity, with the volcanic rocks situated stratigraphically below the sedimentary rocks. In another area, the contact is a thrust fault, with volcanic rocks situated structurally above the sedimentary rocks. Previous studies (Stauffer and Mukherjee, 1971; Bailes and Syme, 1989; Thomas, 1992, 1994) have not focused on the basement-cover contact, and particularly, its dual role as both an unconformity and a thrust fault. Previous structural research (Stauffer and

Figure 1.1. Geology of the Flin Flon area (after Stockwell, 1960; Bailes and Syme, 1989; Syme et al., 1993; Thomas, 1992, 1994). Location of study area is outlined. Dates for the two plutons obtained from Stern and Lucas (1994).

Mukherjee, 1971; Bailes and Syme, 1989; Thomas, 1992, 1994; Fedorowich et al. 1995) has documented the deformation sequence in the Flin Flon area but has either focused only on the volcanic or the sedimentary rocks, without correlating deformation across the intervening contact, or has been concerned with a more regional understanding of the geology.

This thesis documents a detailed examination of the structural geology surrounding Flin Flon, Manitoba (Fig. 1.1). The idea for this study originated from recent mapping conducted by Thomas (1992, 1994, Saskatchewan Energy and Mines) and Bailes and Syme (1989, Manitoba Mines and Energy). The deformation models established during the studies by Thomas (1992, 1994) and Bailes and Syme (1989) differ significantly from each other, indicating unresolved questions regarding the structural history of the Flin Flon area. This study also forms part of an on-going project undertaken by Hudson Bay Exploration and Development (HBED) that focusses on the geology of the Flin Flon and Callinan volcanogenic massive sulphide deposits.

1.2 - Location, access and physiography

The town of Flin Flon is well known in Canada not only for its distinctive name but also because of the 64 Mt Flin Flon Cu-Zn deposit, one of the largest of its kind in Canada. This mining community of 8000 people is situated 750 km north-northwest of Winnipeg, in the northwestern portion of Manitoba, adjacent to the

provincial border with Saskatchewan. Flin Flon can be approached by road from southern Manitoba or from eastern Saskatchewan and is serviced by daily commercial airline flights from the city of Winnipeg.

The numerous roads surrounding the community of Flin Flon provided easy access to the entire study area. HBED permitted the author's access to areas surrounding the mine site and provided data from diamond drill holes collared within the study area.

The physiography of the 15 km² study area (Map 1 and 2, inside back pocket) is typical of the Canadian Shield. Evergreen trees dominate the countryside, combined with isolated stands of poplar and birch. Swamps and marshlands are interspersed within these forested areas. The Flin Flon smelter has been in operation since the 1930's. The construction of a 260 m tall stack in the mid 1970's has allowed rejuvenation of the vegetation that had perished as a result of emissions from the previous 35 m stack. Despite this, the study area shows broad whale-back outcrops with limited vegetation, providing geologists with extensive outcrop (up to 50-60%) in areas close to the stack. In general, outcrop exposure averages 5-15 % throughout the area. Topographic relief in the study area is limited to approximately 65 m, with the volcanic and intrusive rocks, as well as the conglomeratic units, forming topographic highs, and finer grained sedimentary rocks forming topographic lows.

1.3 - Previous Work

The following is a summary of previous work completed in the Flin Flon area. Work within the Flin Flon arc assemblage (formerly known as the Amisk Group; Bruce, 1918) and the unconformably overlying Missi Group sandstones in the Flin Flon area is extensive and dates back to the beginning of this century when mapping was initiated by the Geological Survey of Canada (Tyrrell, 1902; Bruce, 1918). A detailed summary of the structural models generated from some of these studies will be presented in section 2.4.

Ambrose examined the Missi Group (Missi Series; Ambrose, 1936a, 1936b) in a structural and metamorphic study. Ambrose established the initial stratigraphy within the sedimentary basin, which was expanded upon in following studies (e.g., Stauffer and Mukherjee, 1971; Stauffer, 1990 and references therein). He observed a single set of folds with associated planar and linear fabrics, and identified two metamorphic isograds in the Missi Group sedimentary rocks.

Fieldwork by Stockwell in the mid 1940's (Stockwell, 1946) resulted in the publication of a map in 1960 (Stockwell, 1960). This map covered the southern half of the Missi Group basin in the Flin Flon area as well as the volcanic sequence around the Flin Flon mine area. Stockwell (1960) identified numerous macroscopic fold and fault structures but did not discuss the deformational sequence in detail.

Stauffer and Mukherjee (1971) presented a detailed summary of the structural history within the Missi Group at Flin Flon. By examining the relationship between

the pervasive fabric and numerous macroscopic folds, they identified three deformation events. They also calculated displacements for the numerous faults in the Flin Flon area.

Bailes and Syme (1989; Manitoba Energy and Mines) systematically mapped the Flin Flon-White Lake sheet, including the Flin Flon mine area, at 1:20000 scale. In the course of their study of the volcanic stratigraphy and the Missi Group, they established a sequence of five deformation events. The authors correlated the fold generations established by Stauffer and Mukherjee (1971) with those observed in the older volcanic rocks of the Flin Flon arc assemblage.

Thomas (Saskatchewan Energy and Mines) began systematic re-mapping of the Flin Flon area (Saskatchewan) in 1992, focusing on a 30 km² area west of the Flin Flon mine (Thomas, 1992). Mapping continued in 1994 with detailed studies of the volcanic rocks in the footwall to the Flin Flon-Callinan ore horizon (Thomas, 1994). Thomas developed a detailed stratigraphic section of the footwall volcanic and volcanoclastic units, together with a structural synopsis for the area.

Extensive geochronological work has been carried out in the Flin Flon area by K.M. Ansdell, L. M. Heaman and J. David. Ansdell (1993) obtained U-Pb ages for detrital zircons in the Missi Group (Flin Flon sedimentary basin). A minimum age of 1847 ⁺²/₋₂ Ma, combined with an age of 1842 ⁺³/₋₃ Ma for a cross-cutting Boundary Intrusion (Heaman et al. 1992), constrains timing of deposition of Missi strata to within 5 Ma. David et al. (1993) obtained an U/Pb zircon age of 1904 ⁺⁷/₋₄ Ma for the Mine rhyolite at the Flin Flon mine.

Fedorowich (1995) examined the timing of shear zones and regional metamorphism within the central portion of the Flin Flon Belt. Thermochronology of minerals associated with shear zone development and peak metamorphism was used to establish timing of deformation. He demonstrated that peak metamorphism in the Flin Flon area occurred between approximately 1820-1790 Ma.

1.4 - Present study

Fieldwork for the project began in the summer of 1994. During the first half of this field season, the author assisted D.J. Thomas (Thomas, 1994) with mapping the footwall rocks to the Callinan deposit. Fieldwork related to the thesis was started midway through the summer and focused on mapping the hanging-wall rocks to the Callinan and Flin Flon deposits. Airphotos (1:5000 scale) were used as a base for all mapping within the study area. This work was followed by a complete field season in 1995. Initial mapping was focused in the Missi Group sedimentary rocks and concentrated on establishing a deformation sequence by testing existing models against new field observations. Numerous indicators for stratigraphic younging directions, combined with a number of conglomeratic marker horizons, facilitated interpretation of this polydeformed area. The structural model was then applied to the Flin Flon arc assemblage, with the main emphasis on trying to correlate deformation between the two suites of rocks.

The following six points summarize the primary objectives of this thesis:

i) A deformation sequence for the study area has been developed by critically examining established structural models, combined with field observations from the Missi Group sedimentary rocks.

ii) This structural model was then compared to field observations of structures from the Flin Flon arc assemblage volcanic rocks.

iii) The nature of the contact between the Flin Flon arc assemblage and the Missi Group has been examined throughout the study area.

iv) All fabrics observed in the field have been examined at the microscopic level so that overprinting relationships and timing of peak metamorphic mineral growth relative to fabric development could be understood.

v) The local deformation sequence has been compared to regional tectonic events from within the Flin Flon Belt and adjacent areas.

vi) Structural observations from underground workings at the Callinan volcanogenic massive sulphide (VMS) deposit have been compared to the model generated from surface mapping.

1.5 - Outline of thesis

Chapter 2 is a summary of the previous work completed within the Flin Flon area. It includes the regional and local geology, together with a structural synopsis of current deformation models and a description of the metamorphism. Chapter 3 is a detailed description and interpretation of the structural geology of the Flin Flon area.

Chapter 4 is the final discussion and summarizes the deformation history of the Flin Flon area. This deformation model is compared to both the regional tectonic setting and to the geology of the Callinan mine.

◆ Chapter 2 - Geological Summary ◆

2.1 - Regional Geology

Flin Flon is situated within the northwestern segment of the Trans-Hudson Orogen (THO) of the Canadian Shield. This orogenic belt is part of a larger orogenic system that was created during Paleoproterozoic collisions between the Archean cratons depicted in Figure 2.1 (inset; Hioffman, 1988). South of Flin Flon, the THO extends beneath the Paleozoic cover sequence as far as South Dakota, where it is truncated by the Central Plains Orogen (inset, Fig. 2.1; Sims and Peterman, 1986). To the north, the THO adopts a northeasterly trend and continues beneath the Phanerozoic Hudson Bay basin into northern Quebec and southern Baffin Island. Recent bedrock mapping projects undertaken by the Manitoba and Saskatchewan Geological Surveys, combined with the NATMAP Shield Margin Project and LITHOPROBE THO Transect in Manitoba and Saskatchewan, have significantly improved the understanding of the geology, crustal structure and tectonic evolution in the northwestern segment of this orogen. This segment of the THO has been broken down into a number of mainly juvenile, intraoceanic Paleoproterozoic terranes collectively known as the Reindeer Zone (Fig. 2.1; Stauffer, 1984; Bickford et al, 1990). The Flin Flon Belt, one of the juvenile terranes, is bounded to the west by the Tabbernor fault, and to the north and east by the Kisseynew Domain (Fig. 2.2). It extends southward beneath the Paleozoic cover sequence (Leclair et al., 1997), which

Figure 2.1. Map of the Trans-Hudson orogen, after Hoffman (1988). W: location of Archean basement windows in the Reindeer Zone; FFB: Flin Flon Belt; GD: Glennie Domain; HLB: Hanson Lake block; LRD: La Ronge Belt; Kiseknew Domain; SSKD: southern flank of Kiseknew Domain; RD: Rottenstone Domain; TB: Thompson Belt; TF: Tabbemor fault zone; WB: Wathman-Chipewyan batholith. The location of Figure 2.2 is indicated. Inset shows the extent of THO in North America and location of Figure 2.1.

TECTONIC MAP of the FLIN FLON and KISSEYNEW BELTS

SUCCESSOR ARC & BASIN DEPOSITS

- MISSI GROUP (1.83-1.85 Ga)
- BURNTWOOD GROUP (1.84 - 1.85 Ga.)
- *** SCHIST-WEKUSKO VOLCANICS (1.85-1.88 Ga)

FELSIC-MAFIC PLUTONS

- <1.80 Ga
- 1.80-1.84 Ga
- >1.84 Ga

FAULT ■ VMS deposit

PRE-ACCRETION ASSEMBLAGES (1.87 - 1.92 Ga)

- JUVENILE ARC ASSEMBLAGES
- OCEAN FLOOR ASSEMBLAGES
- ★ OCEAN ISLAND ASSEMBLAGE
- OCEAN PLATEAU ASSEMBLAGE
- EVOLVED ARC ASSEMBLAGE

PELICAN WINDOW AND DÉCOLLEMENT ZONE

- ARCHEAN / PELITIC GNEISS
- SHEARED JUVENILE ARC ASSEMBLAGE

Figure 2.2 After Stern et al. (1995a, b) and Lucas et al., (1995), modified by Zwanzig (pers. com., 1997). Map of the Flin Flon Belt showing major tectono-stratigraphic assemblages and plutons. The Flin Flon Belt is structurally below the overriding south flank of the Kisseynew Domain and above the Hanson Lake block. Location of Figure 2.3 is indicated. HLB: Hanson Lake block; SWsz: Sturgeon Weir shear zone.

occurs 40-50 km south of the town of Flin Flon. LITHOPROBE seismic reflection profiles across the region have revealed the three-dimensional crustal-scale structure of the area (Lucas et al., 1994; White et al., 1994).

The Hanson Lake "block" (Fig. 2.2), representing the western portion of the Flin Flon Belt, consists of a greenschist to upper amphibolite facies volcano-plutonic package of 1890-1840 Ma. rocks (Heaman et al., 1994). It is structurally underlain by a granulite facies suite of Archean rocks (Sask Craton; Heaman et al., 1995) exposed in the Pelican Window (Lewry et al., 1989). The contact between these two suites is marked by a 5-10 km wide mylonite zone (labelled Sheared Juvenile Arc Assemblage, Fig. 2.2) termed the Pelican Decollement Zone (Ashton and Lewry, 1996), which accommodated the southwestwardly-directed thrusting of the Flin Flon Belt and Kiseynew Domain over the Archean rocks (Lewry et al., 1990; Ashton and Lewry, 1996). The Sturgeon-Weir shear zone (Fig. 2.2) was previously believed to separate the Hanson Lake "block" from the Flin Flon Belt, but has since been re-interpreted as a late splay, rooted in the Pelican Decollement Zone (Ashton and Lewry, 1996).

To the north of the Flin Flon Belt lies the Kiseynew Domain which is dominated by amphibolite-grade migmatitic gneisses and schists derived from a thick sequence of turbiditic greywackes (Burntwood Group; Zwanzig, 1990). The rocks of the Kiseynew Domain have been dated at 1850-1840 Ma (David et al., 1996), and are therefore in contrast to the 1920-1870 Ma volcanic rocks of the Flin Flon Belt and the Hanson Lake "block". Ansdell et al. (1995; cf. Gordon, 1989) postulated that the

turbidites were deposited in a basin marginal to the Flin Flon Belt.

The following summary of the Flin Flon Belt is taken from Lucas et al. (1996), who describe the complex history of this region. The Flin Flon Belt is a collage of distinct tectonostratigraphic assemblages that were amalgamated at a relatively early stage in the evolution of the Paleoproterozoic Trans-Hudson Orogen (Stern et al., 1995a, b; Lucas et al., 1996). These assemblages (1920-1870 Ma.) include juvenile arc, ocean floor, ocean island, ocean plateau, as well as limited arc segments built on Archean crust (Fig. 2.2), and are thought to have formed in an intra-oceanic tectonic setting. These assemblages were amalgamated (1880-1870 Ma.) to form the Amisk Collage (central Flin Flon Belt), intruded by numerous plutons (1870-1840 Ma.) and unconformably overlain by sedimentary and volcanic rocks (1870-1840 Ma.). The younger magmatic rocks post-dating accretion are interpreted to represent successor arcs, built on the older assemblages and associated with continued subduction in a convergent-margin tectonic setting. The majority of the Flin Flon Belt was metamorphosed to greenschist facies conditions during the peak metamorphic event at 1820-1790 Ma. (Gordon et al. 1990; Ansdell and Norman 1995; Fedorowich et al., 1995; David et al. 1996). This thermal peak is interpreted to be coincident with collision between the Flin Flon Belt and the Archean Sask craton (Ansdell et al. 1995; Heaman et al., 1995).

Seismic transects conducted by LITHOPROBE provide a three-dimensional insight into the nature of the boundaries between the Sask craton basement, the Kiseynew Domain and the Flin Flon Belt, as well as on the major structures that

dissect these three areas internally (Lucas et al., 1993a, 1994; Lewry et al., 1994; White et al., 1994). Profiles across the eastern segment of the Reindeer Zone show continuous north- to east-dipping reflectors which extend to the base of the crust (Lucas et al., 1993a; White et al., 1994). These observations (cf. Lucas et al., 1994) support models derived from bedrock mapping that describe southwestwardly-directed thrusting of the Kiseeynew Domain and the Flin Flon Belt over the Archean Sask craton (Lewry et al., 1990; Ashton and Lewry, 1996; Zwanzig, 1990; Norman et al., 1995; Connors, 1996).

2.2 - Local Geology

The geology within the study area consists of three main elements: (1) the Flin Flon metavolcanic arc assemblage, which is host to the Flin Flon and Callinan volcanogenic massive sulphide (VMS) deposits; (2) the unconformably overlying metasedimentary Missi Group; and (3) the Boundary Intrusions, a set of post-Missi Group felsic to mafic plutonic rocks. All three lithologic types discussed are metamorphosed, but the prefix 'meta' has been omitted for simplicity.

2.2.1 - Flin Flon arc assemblage

The volcanic rocks of the Flin Flon Belt have been divided into a number of different assemblages on the basis of extensive geological, geochemical and isotopic data (Syme and Bailes, 1993; Stern et al., 1995a, b; Fig. 2.2). The volcanic material

around Flin Flon was formerly known as the Amisk Group but is now labelled the Flin Flon arc assemblage (Bruce, 1918; cf. discussion in Lucas et al., 1996). Figure 2.2 shows some of the VMS deposits that have been mined within the Flin Flon-Snow Lake Belt. All of these deposits occur solely within the juvenile arc assemblages and the Flin Flon and Callinan VMS deposits are no exception (Syme and Bailes, 1993). Geologists from the Manitoba and Saskatchewan Geological Surveys have published reports that summarize the detailed stratigraphy surrounding these two deposits (i.e., Syme and Bailes, 1993; Thomas, 1994) and the geology in the southern Flin Flon area (i.e. Thomas, 1992).

Syme and Bailes (1993) described the geology in the footwall and hanging-wall of the Flin Flon deposit (Fig. 2.3, 2.4). The South Main basalt forms the base of the footwall sequence in the immediate mine area and can be observed in outcrop southeast of Flin Flon Lake (Fig. 2.3). It is composed mainly of pillowed flows and associated flow-top amoeboid pillow breccia that grade upwards into the South Main pillow fragment breccia. This breccia unit underlies the deposit and is monolithologic, poorly sorted, clast-supported and massive. A unit of plagioclase-porphyritic mafic volcanoclastic rocks is found within the fragment breccia and consists of a heterolithic breccia which is thickly bedded, poorly sorted and fragment-supported. The alteration present throughout these footwall rocks consists of intense epidotization, accompanied by local zones of chloritization and sericitization. Above these footwall assemblages, forming a 150 m thick sequence, is the Mine rhyolite. It is composed internally of two separate flows, based on size and abundance of

Figure 2.3. Geology of the Flin Flon area (after Stockwell, 1960; Bailes and Syme, 1989; Syme et al., 1993; Thomas, 1992, 1994). Dates for the two plutons obtained from Stern and Lucas (1994).

Figure 2.4. Stratigraphy of study area. North-south cross section of Flin Flon mine stratigraphy modified from Syme and Bailes (1993). Flin Flon basin stratigraphy modified from Stauffer (1990).

phenocrysts, and is the host to the Flin Flon massive sulphide deposit. Recent detailed geochronological, geochemical and isotopic studies of the volcanic stratigraphy at Flin Flon have shown that the Mine rhyolite is $1904 \pm 7/4$ Ma (U-Pb zircon; David et al., 1993), and that the strata which constitute the hanging-wall and footwall are part of a suite of isotopically juvenile island-arc tholeiites (Syme and Bailes, 1993; Stern et al., 1995a). In the hanging-wall immediately above the Mine rhyolite is a thin felsic volcanoclastic unit termed the Railway volcanoclastics. The 3 km thick Hidden Lake basalt sequence lies above these volcanoclastic rocks and consists of pillowed flows with associated amoeboid flow breccias (Fig. 2.4; Plate 2.1).

Thomas (1994) examined the rocks in the footwall to the Callinan deposit north of Flin Flon Lake (Fig. 2.3). The base of the footwall stratigraphy is composed of highly amygdaloidal pillowed basalt flows and amoeboid pillow breccias. The Club Lake felsic eruptive unit lies above this unit and includes mixed rhyolitic flows and volcanoclastic rocks. Two separate rhyolite flows are recognized within this unit and are variably aphyric, quartz or quartz-feldspar phyric. These felsic rocks underlie the Footwall Volcanoclastic unit, which is a thick (~250 m) sequence of mafic pyroclastic and re-sedimented syn-eruptive volcanoclastic rocks. Alteration throughout the footwall rocks is shown by an increase in epidote, plagioclase and quartz, and a depletion of ferromagnesian minerals. A quartz-phyric rhyolite is found conformably above this unit and is the surface projection of the upper Callinan porphyry. The hanging-wall sequence is composed largely of a thick pile of aphyric and feldspar-

Plate 2.1: Mafic pillow basalts grading into flow-top amoeboid pillow breccia from the eastern limb of the Hidden Lake synform, south of the South Railway fault. Stratigraphic facing direction, shown by pillow shapes and amoeboid flow top, is towards base of photo. Clipboard is 30 cm in length and the view is to the northeast.

Plate 2.2: Well-preserved unconformity between Flin Flon arc assemblage and Missi Group, from the southwestern corner of the study area (400 m southeast of Louis Lake). Rounded mafic flow fragments (FFaa) underlie the conglomerate (Missi). Clipboard is 30 cm in length and is located at the basement-cover contact. View is towards the east.

Plate 2.1

Plate 2.2

phyric pillowed and massive flows of the Hidden Lake sequence (Bailes and Syme, 1989).

Thomas (1994) did not attempt to correlate the stratigraphy he identified north of Flin Flon Lake with the stratigraphy that Bailes and Syme (1989) identified in the Flin Flon mine area. Tentative correlations can be made by comparing the two stratigraphic sequences. Thomas's (1994) footwall section consists mainly of volcanoclastic rocks, with interspersed felsic and mafic flows, and is estimated to represent a 500 m thick section below the Callinan mine horizon. Bailes and Syme (1989) mapped a much thicker pile of rock beneath the Flin Flon deposit (> 1400 m). The rocks 500 m stratigraphically below the Flin Flon deposit are volcanoclastic rocks (300 m thick) and the underlying South Main pillow fragment breccia (400 m thick). Therefore, a correlation can be made on the basis of the fragmental rocks that compose the footwall of each stratigraphic sequence. Thomas (1994) states that the Callinan porphyry is correlative with the felsic rocks that compose the Mine rhyolite (Bailes and Syme, 1989), and that the basalts within his hanging-wall sequence are correlative with the Hidden Lake basalts (Bailes and Syme, 1989).

Thomas (1992) mapped the volcanic rocks surrounding Louis Lake and the Missi Outlier (southern study area; see Fig. 2.5, below) and described them as massive or pillowed, aphyric to plagioclase-phyric mafic flows, with minor flow breccia.

All of these volcanic rocks are overlain by a variably preserved paleo-weathered (regolith) horizon extending up to 10 m below an unconformity at the base

of the Missi Group (see Plate 2.2; Bailes and Syme, 1989; Holland et al., 1989; Stauffer, 1990). It typically consists of rounded mafic clasts and epidosite fragments, some of which exhibit characteristic spheroidal weathering with well-developed "onion-skin" structures (Stauffer, 1990).

2.2.2 - Missi Group

Unconformably overlying the volcanic rocks is the Missi Group (Bruce, 1918; Bailes and Syme, 1989; Stauffer, 1990; Fig. 2.3), a package of continental fluvial sedimentary rocks which are preserved in isolated structural basins throughout the Flin Flon Belt and northward into the Kiseynew Domain. The stratigraphy of the Missi Group at Flin Flon was first established by Ambrose (1936a) and developed further by Stauffer and Mukherjee (1971) and Stauffer (1990). At Flin Flon, Missi Group conglomerates and sandstones were deposited at ca. 1845 Ma., bracketed by the youngest detrital zircon ($1847 \pm 2/2$ Ma; Ansdell et al., 1992; Ansdell, 1993) and the oldest cross-cutting intrusion ($1842 \pm 3/3$ Ma Boundary Intrusion; Heaman et al., 1992). The Missi Group at Flin Flon consists of two fining-upward members, the lower Beaverdam and upper Little Cliff Members, which are each divided into 3 separate units (Fig. 2.4; Stauffer, 1990). Each member is interpreted to represent a transition from a proximal fan to a braided-stream environment. In the field, the divisions between the six units are gradational and depend on clast percentages. The clasts are largely of mafic origin in the Beaverdam Member and increase in felsic proportion in the Little Cliff Member, reflecting a contrast in specific source area

between the respective units (Stauffer, 1990).

The Beaverdam Member can be divided into three separate units, beginning with a basal, polymictic conglomerate unit (Plate 2.3), considered to be an alluvial fan or proximal braided-stream deposit. Unit 2 consists of pebbly sandstones, considered to be of mid-fan to braided-stream origin. Unit 3 consists of clast-poor sandstones, suggested to be a distal braided stream deposit. Within unit (3) there are isolated 3-5 m thick conglomerate beds, dominated by sub-angular quartz fragments (e.g. Mud Lake syncline area, see Fig. 2.5). The Beaverdam Member is up to 1600 m thick, of which unit 3 is the major part. The Little Cliff Member is composed of similar rocks, showing the same sequence of depositional environments, but with a maximum thickness of only 600 m. Unit 4 is a polymictic conglomerate, unit 5 is pebbly sandstone (Plate 2.4) and the uppermost unit (6) is sandstone (Stauffer, 1990). Using the classification scheme of Pettijohn et al. (1972), Stauffer (1990) concluded that most of the Missi material was probably deposited as sublithic arenite to subarkose, with minor quartz arenite and lithic to arkosic arenite beds. Cross-bedding is preserved in all units and has been used extensively in the present study to determine stratigraphic younging directions.

2.2.3 - Boundary Intrusions

The Boundary Intrusions were originally defined by Stockwell (1960) and form a series of elongated, lensoid and dyke-like bodies that intrude the Flin Flon arc assemblage and the Missi Group (Maps 1 and 2, inside back pocket). Syme and

Plate 2.3: The basal, polymictic conglomerate unit within the Missi Group, south of Ross Lake. Rock is dominated by mafic fragments, with minor quartz, rhyolite and granitoid clasts. Paleospheroidal weathering is preserved within some of the fragments (Onion-skin texture within clast in exact centre of photo). Pen is 15 cm in length and trends southeast-northwest.

Plate 2.4: Pebble beds with cross-bedding (unit 5; Stauffer, 1990) from northeastern limb of the Pipeline syncline. Stratigraphic facing direction is towards top of photo (west). Pen is 15 cm in length and trends southeast-northwest.

Plate 2.3

Plate 2.4

Forester (1977) completed a detailed study of these intrusions and identified three, compositionally distinct groups. From oldest to youngest these are 1) a mafic group, ranging from pyroxenite and augite mela-diorite to hornblende mela-diorite; 2) a felsic group ranging from leuco-diorite to granodiorite that intrudes the mafic group; and 3) an olivine-bearing group, ranging from peridotite (wehrlite) to olivine gabbro. These rocks intrude both the Flin Flon arc assemblage and the Missi Group and one body has been dated at 1842 ± 3 Ma (Heaman et al., 1992, 1993). A recent study by O'Hanley and Kyser (1994) focussed on trying to determine the provenance of the mafic and ultramafic groups. Isotopic evidence suggests that these mafic and ultramafic intrusions have a similar source, were generated in an island arc setting and were contaminated by surrounding supracrustal rocks during emplacement (O'Hanley and Kyser, 1994). An absence of an Archean signature in the Rb-Sr and Sm-Nd isotopic systems was interpreted to suggest that final tectonic emplacement of the Flin Flon Belt over the Archean rocks postdated ca. 1840 Ma, which is the crystallization age for the Boundary Intrusions (O'Hanley and Kyser, 1994).

2.3 - Local structural geology

As mentioned above, a number of previous studies have examined the structural history of the Flin Flon area. Table 1 presents four structural models (Stauffer and Mukherjee, 1971; Bailes and Syme, 1989; Thomas, 1992, 1994; Fedorowich et al., 1995) and compares them with the deformation sequence from this

Stauffer and Mukherjee, 1971; Missi sediments	Bailes and Syme, 1989; Flin Flon Domain.	Fedorowich et al., 1995; Flin Flon Domain	Thomas, 1992, 1994; Amisk Group (Flin Flon a.a.).	Gale, this study; Flin Flon a.a. and Missi sediments.
Did not map within Amisk Group.	P ₁ N- to NE-trending, tight to isoclinal folds in Amisk Group rocks. No foliation. BLs.	P ₁ Pre-Missi deformation; conjugate arrays of hydrothermal veins truncated at the unconformity.	Not recognized.	Pre-Missi Group N- to NE-trending, tight to isoclinal folds in Amisk Group rocks. No foliation. BLs.
P ₁ Tightly-closed to isoclinal, V- to box-shaped folds. Axial planes vary due to refolding. No foliation. FFCs, RCa, RCs.	P ₂ Post-Missi, originally E-W trending thrusts and gently plunging F ₂ folds. No foliation. CLsz, Rsz and SHsz. FFCs, RCa, RCs.	P ₂ E- to ESE-trending, open to tight folds in Missi Group rocks. No foliation. FFCs, RCs, SHsz, Rsz, SRsz and CLsz.	D ₁ E- and SE- trending, tight to isoclinal folds in Amisk and Missi Groups. Variably-preserved foliation. FFCs, RCs and BLs; CLsz.	D ₁ N/NE-verging F ₁ folds of Amisk and Missi Groups. Rare cleavage. FFCs, RCa, RCs and Missi Outlier. CLsz, Rsz, SRsz, SHsz.
Not recognized.	P ₃ N- and NE- trending, open to tight folds in the Amisk Group. Steeply NE-dipping foliation. <u>HLs</u>	Not recognized.	Not recognized.	Not recognized.
P₂ Tightly-closed, asymmetric, V- to box-shaped folds with pervasive axial planar foliation and lineation. Peak metamorphism.	P₄ N-trending, moderately open folds in Missi Group rocks. Peak metamorphism. Pervasive foliation and lineation. Ps and MLs	P₃ Isoclinal, moderately plunging N-S trending F ₃ folds, oblique-slip shear zones and peak metamorphism. Pervasive foliation and lineation. <u>HLs</u> , Ps, MLs and Cf.	Did not map extensively within the Missi Group.	D₂ <u>HLs</u> . No cleavage. W-verging folds of Amisk and Missi Groups. Pervasive foliation and lineation. MLs + Ps. Peak-metamorphism.
Not recognized	Corresponding structures observed in other studies were assigned a P ₃ age during this study (see above).	P ₄ Not recognized within the Flin Flon area.	D ₂ N-, NNW and NNE-trending tight folds in Amisk and Missi Groups. NE-dipping foliation. <u>HLs</u> .	D ₃ Upright NW-trending folds. Spaced cleavage. High-angle, NW-striking faults. CLf.
P ₃ NNW-trending faults. RLf, CLf	P ₃ Major NNW-trending faults including block bounding faults.	P ₃ Late brittle oblique-slip faults; RLf.	D ₃ Major N- and NNW-trending faults. CLf and RLf.	D ₄ High-angle, oblique-slip faulting. RLf, Cf.

Table 1. Summary of deformational models from the Flin Flon Area. FF a.a.: Flin Flon arc assemblage, FFCs: Flin Flon Creek syncline, RCa and s: Ross Creek anticline and syncline, CL-, R-, SR- and SHsz: Club Lake, Railway, South Railway and Sepple Hill shear zones, BLs: Burley Lake syncline, HLs: Hidden Lake synform, Ps: Pipeline syncline, MLs: Mud Lake syncline, RLf: Ross Lake fault, Cf: Channing fault; CLf: Cliff Lake fault. Icon (~~P~~) signifies pervasive foliation and peak metamorphism.

study. The five structural models vary in their classification of fold generations, interpretation of pre-Missi Group deformation and the total number of deformation events affecting the area. Figure 2.5 shows the locations and relationships of the structures referred to in Table 1, without any new data from this study. A second version of this figure showing new features and some re-interpretations will be provided in the following chapter (Fig. 3.1, below).

Bailes and Syme (1989) identified an early generation of folds which they interpreted to pre-date deposition of the Missi Group. They describe the Burley Lake syncline (Stockwell, 1960), located in the southwestern corner of the field area, as a fold which is truncated at the unconformity (Figure 2.5). Thomas (1992) disagreed with Bailes and Syme, and concluded that the Burley Lake syncline is related to the Ross Creek syncline, a fold observed in the Missi Group sedimentary rocks to the east (c.f. Stauffer, 1990). Fedorowich et al. (1995) observed conjugate arrays of hydrothermal veins, also truncated at the unconformity, and concluded that a period of deformation occurred prior to Missi Group sedimentation. Stauffer and Mukherjee (1971) did not examine structures within the Flin Flon arc assemblage. The Burley Lake syncline area was examined during this study and will be discussed in the following chapter.

Concordance between all five deformation models is shown for the next event (D_1 , this study) which involves folding and faulting in both basement and cover sequences. Table 1 lists the folds and shear zones that developed during this deformation event. Prior to Thomas (1994), evidence for folding during this event

Figure 2.5. Structural geology of the study area. Location of axial-surface traces from Stockwell (1960), Stauffer and Mukherjee (1971), Bailes and Syme (1989) and Thomas (1992). RCs: Ross Creek syncline; RLa: Ross Lake anticline.

had only been recognized within the Missi Group (Stauffer and Mukherjee, 1971). Thomas (1994) identified early east-west trending folds and an associated cleavage developed in two rhyolite horizons in the footwall of the Callinan deposit (Fig. 2.3). The maximum age of this event, as well as all subsequent deformation, is constrained by the Boundary Intrusions ($1842 \pm 3/_{-3}$ Ma; Heaman et al., 1992) which show evidence for D_1 (this study) deformation. The detailed field relationships for all of these structures will be discussed in chapter 3.

Bailes and Syme (1989) proposed a folding event that is only developed within the Flin Flon arc assemblage, but that post-dates deposition of the Missi Group. Their interpretation is based on the Hidden Lake synform (Fig. 2.5), an important fold that is variably interpreted within three of the five structural models. This fold was examined in detail during this study and conclusions regarding its specific generation are presented in chapter 3.

All models, with the exception of Thomas (1992, 1994), relate the next generation of structures (D_2 , this study) to peak metamorphism (Table 1). Thomas (1992, 1994) did not correlate a specific fabric with the peak metamorphic event. Deformation during the D_2 event (this study) produced both a pervasive foliation and a lineation that are observed throughout most of the study area. The age of this event has been constrained regionally by the dating of minerals associated with peak metamorphic assemblages (1820-1790 Ma.; Gordon et al., 1990; Ansdell and Norman, 1995; Heaman et al., 1995; David et al., 1996; Fedorowich, 1995).

A third ductile deformation event, represented by a cleavage, rare folds and

shear zone development, was recognized in this study (D_3 , this study). Thomas (1992, 1994) recognized the same cleavage but associated it with the Hidden Lake synform. Bailes and Syme (1989) also identified this same cleavage but interpreted it as pre-dating the pervasive foliation associated with peak metamorphism (i.e. S_2 , this study). Regionally extensive shear zones developed initially during this event (e.g. Cliff Lake fault; Stauffer and Mukherjee, 1971) and experienced a protracted period of deformation, which continued until 1690 Ma (D_4 , this study; e.g. Ross Lake fault; Stauffer and Mukherjee, 1971; Fedorowich et al., 1995).

A number of issues arise from the structural synopsis presented in Table 1. Evidence for pre-Missi Group deformation in the Flin Flon area, in part, depends on the age of the Burley Lake syncline. This structure has been associated with both pre- and post-Missi Group deformation events. The cleavage relationships between the pervasive peak metamorphic foliation (S_2 , this study) and the northwest striking, steeply-northeast dipping foliation (S_3 , this study) are variably interpreted. Also, three different models for the Hidden Lake synform are presented. These conflicting relationships will be addressed in chapter 3.

2.4 - Metamorphism

The Flin Flon arc assemblage and Missi Group were metamorphosed at sub-greenschist to lower amphibolite grade conditions during pervasive cleavage development (D_2 this study; Ambrose, 1936b; Bailes and Syme, 1989; Digel and

Gordon, 1995). Fedorowich et al. (1995) present biotite and hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ data which indicate that peak metamorphism occurred at 1820-1790 Ma in the Flin Flon area, coeval with regional peak metamorphism and deformation across the Trans-Hudson Orogen (e.g., Gordon et al., 1990; Ansdell and Norman, 1995; Heaman et al., 1995; David et al., 1996). Digel and Gordon (1995) completed a study of metamorphism within volcanic rocks from the Flin Flon area and identified a number of isograds (south to north: the hornblende-in, actinolite-out and epidote and chlorite-out isograds) within the greenschist and lower amphibolite facies (Fig. 2.3). Ambrose (1936b) and Stauffer and Mukherjee (1971) completed similar analyses of metamorphism within rocks of the Missi Group (chlorite-out, biotite-in isograd; Fig 2.3). Metamorphic minerals observed during the present study are generally consistent with these established isograds and will be discussed in chapter 3.

◆ Chapter 3 - Structural Geology ●

3.1 - Introduction

The following chapter presents observations and interpretations from several areas around Flin Flon. To describe all of these structures, the study area has been divided into two regions that are depicted on Figure 3.1 (northern and southern) and that correspond to Maps 1 and 2 (inside back cover). The structural and metamorphic relationships of these two regions will be discussed separately. Figure 3.1 also shows all of the features identified during this study, together with re-interpretations of the pre-existing structures that were shown on Figure 2.5.

All stereonet data presented throughout the text were plotted using the structural program Quickplot. The maps were produced by using Autocad with a GSC Fieldlog v2.83 interface. A three dimensional model of the northern field area was constructed using gOcad®.

3.2 - Structures in the southern region

The description of the southern region (Fig. 3.1) is divided into six sections (Missi Outlier, Ross Creek syncline, Mud Lake syncline, relationships at the basement-cover contact, Burley Lake syncline and Sepple Hill shear zone), followed by a discussion on microscopic relationships.

Figure 3.1. Structural geology of the study area. Location of axial surface traces from this study, Stockwell (1960), Stauffer and Mukherjee (1971), Bailes and Syme (1989) and Thomas (1992). RCs: Ross Creek syncline; RLa: Ross Lake anticline.

3.2.1 - Missi Outlier

A small outlier of Missi Group sedimentary rocks occurs just to the south of the principal Missi basin, and contains evidence for all three deformation events (Fig. 3.1, 3.2). This structure was mapped by Stockwell (1960) and Bailes and Syme (1989) but the detailed structural relationships discussed below have not been previously documented. Macroscopic folds are easily delineated by tracing a distinctive conglomerate unit in the dominant facies of pebbly sandstone, while mesoscopic folds are well developed in beds containing centimetre-scale hematite laminations.

Bailes and Syme (1989) identified an east-west trending fold (here designated F_1) within this outlier. The earliest recognizable foliation (designated S_1) is an axial-planar cleavage, that is only developed in rare, fine-grained shale lenses between sandstone beds and in the regolith at the unconformity (Plate 3.1). The S_1 cleavage is crenulated by a second cleavage (designated S_2 ; Plate 3.1) that is axial planar to closed to tight folds (designated F_2), which trend north and have axial planes that dip moderately to steeply to the east. A third cleavage, defined by flattened quartz grains and aligned micas, is heterogeneously developed throughout the outlier (Plate 3.1). This cleavage (designated S_3) strikes northwest and dips steeply to the northeast, but is not obviously related to any macroscopic folds in the outlier. Clasts within the sandstone and conglomerate beds are flattened in S_2 where S_3 is absent, but are aligned in S_3 where it is developed.

The outlier's basinal shape is inferred to have resulted from type-I - type-II

Figure 3.2. The Missi Outlier from the southern portion of then study area. Map shows S_0 , S_1 , S_2 and S_3 relationships and includes a north-south oriented vertical cross section.

Plate 3.1: Overprinting cleavage relations (S_1 , S_2 and S_3) from within the Missi

Outlier. Lense of shale within the sandstone shows the S_1 cleavage. S_2 crenulates the S_1 and is pervasively developed throughout the rock. S_3 is a spaced foliation that overprints the two earlier fabrics. Length of pen visible is 7 cm.

Plate 3.2: Conglomerate bed (unit 3; Stauffer, 1990) from the core of the Mud Lake

syncline. Clasts consist almost entirely of quartz, with minor mafic and granitoid fragments. Cross-bedding preserved below the conglomerate indicates that stratigraphic younging is towards top of photo. Pen is in centre-left of photo and is 15 cm in length. View is to the southeast.

Plate 3.1

Plate 3.2

interference (Ramsay, 1967) between F_1 and F_2 folds. The F_1 fold closure is faulted out on the western limb of the F_2 fold (Fig. 3.2). The eastern F_1 closure is calculated to plunge 68° towards 021° (Fig. 3.3) and is now an F_1 antiformal syncline, overturned during F_2 deformation (Fig. 3.2). The macroscopic F_1 syncline trends east-west (Fig. 3.2) and has a southerly overturned northern limb on the east side of the F_2 fold. The southern F_1 limb generally dips moderately to the north but is locally overturned, dipping steeply to the south due to F_2 folding (Fig. 3.2). The original F_1 fold orientation is difficult to determine because of F_2 overprinting deformation but, based on the orientation of bedding on the western side of the F_2 axial plane (Fig. 3.2), it must have been an upright fold. As illustrated by the map pattern and cross-section (Fig. 3.2), the F_1 fold is asymmetric, with more section on the southern limb than on the northern one. This, coupled with the changing stratigraphic position of the conglomeratic bed relative to basement along strike (Fig. 3.2), may well reflect deposition controlled by topography on the basement erosion surface.

3.2.2 - Ross Creek syncline

Stauffer and Mukherjee (1971) proposed the existence of the Ross Creek syncline (Fig. 3.1) based on a number of field relationships. The clearest evidence for this structure occurs between Ross Lake and Channing faults, where poles to bedding traces define a fold axis plunging 45° towards 072° and an axial plane that is either vertical or dips steeply to the north (Stauffer and Mukherjee, 1971). A plot of poles to bedding planes measured during this study defines a fold hinge calculated to

Figure 3.3. S_2 cleavage traces (with dip indicated) for the study area, with equal area stereonet plots showing S_0 data.

plunge 36° towards 080° (Fig. 3.3) and an axial plane that strikes 090° and dips 80° south. The Ross Creek syncline is inferred to be an F_1 structure because a pervasive cleavage (designated S_2) transects both of its limbs (Stauffer and Mukherjee, 1971).

A second piece of evidence for the Ross Creek syncline is observed to the west of Ross Lake fault, where the basement-cover contact dips to the north in the southern portion of the Missi Group sedimentary basin and to the south in the Ross Lake area (Fig. 3.1; Stauffer and Mukherjee, 1971). Stauffer and Mukherjee (1971) show the axial trace of the Ross Creek syncline continuing westward until it abuts against the unconformity (Fig. 3.1).

A third piece of evidence for the Ross Creek syncline is found east of the Channing fault where the Mud Lake syncline (F_2 , see below; Fig 3.1) is doubly plunging (Stauffer and Mukherjee, 1971). The Ross Creek syncline is interpreted to cross the Mud Lake syncline and become an antiformal syncline on the overturned eastern F_2 fold limb (Stauffer and Mukherjee, 1971). These relationships in the core of the Mud Lake syncline will be discussed in the following section.

3.2.3 - Mud Lake syncline

The Mud Lake syncline is outlined by three conglomerate horizons which form a basinal shape northwest of Mud Lake (Fig. 3.1). These conglomerate marker beds are part of the upper sandstone unit (3) within the Beaverdam Lake Member (see plate 3.2; Fig. 2.4; Stauffer, 1990). The western limb of this syncline dips moderately (30° - 60°) to the east and the eastern limb dips steeply (50° - 80°) to the west, with beds

locally overturned (75° - 85°) to the east (Stauffer and Mukherjee, 1971). This doubly plunging fold has a plunge reversal from the northern hinge (plunging 13° towards 162°) to the southern hinge (plunging 8° towards 347°), based on poles to bedding planes from the upper two conglomerate horizons observed in this study (Fig. 3.3).

A dominant, pervasive foliation is developed throughout the Mud Lake area and is axial planar to the Mud Lake syncline (Fig. 3.4). This foliation (designated S_2 based on regional cross-cutting of F_1/S_1 structures) corresponds to the pervasive fabric that overprints the F_1 Ross Creek syncline just west of the Channing fault (Stauffer and Mukherjee, 1971). An early foliation (S_1) pre-dating S_2 is not observed in this area, but there is cryptic evidence for early, east-west folds (F_1) that are overprinted by the S_2 cleavage. These structures are preserved in small, 10-20 cm sized, type-I - type-II interference basins (Ramsey, 1967) shown by shale and hematite laminations within the sandstone (Plate 3.3). In these structures, earlier east-west folds are overprinted by north-south folds with S_2 as their axial-planar cleavage. There is a very poorly developed extension lineation in the Mud Lake interference basin with a mean attitude plunging 20° towards 138° (Fig. 3.4). Based on observations from the northern region and previous interpretations, this lineation is associated with the second deformation event (L_2 ; Stauffer and Mukherjee, 1971).

Another foliation that deforms the S_2 was observed in the Mud Lake area during this study (designated S_3). It is well developed and is axial planar to centimetre-scale, open, upright folds (F_3) of bedding, which have a mean axial plane striking 328° and dipping 65° northeast (Plate 3.4; Fig. 3.5).

Plate 3.3: Type-II fold interference structure from Mud Lake syncline area. The folds are defined by hematite laminations within unit 3 (Stauffer, 1990) sandstone. S_2 cleavage is axial planar to the F_2 fold, which deforms the originally east-west striking F_1 fold. Pen tip is 3 cm in length and is striking north-south.

Plate 3.4: Spaced S_3 cleavage axial planar to folded hematite laminations, western limb of Mud Lake syncline. Pen is 15 cm in length and is aligned in the S_3 foliation plane. View is to the southeast.

Plate 3.3

Plate 3.4

Figure 3.5. S_2 cleavage traces (with dip indicated) for the study area, with associated equal area stereonet plots. A synoptic plot of L_2 data from across the study area is shown in upper right corner.

The plunge reversal defined by bedding in the core of the Mud Lake syncline is gentle enough to not require an earlier cross structure (F_1) and could be attributed to non-cylindrical F_2 folding. However, multiple mesoscopic F_1 folds observed within the Mud Lake basin suggest that there was a folding event (F_1) prior to development of the Mud Lake syncline (F_2). These observations support Stauffer and Mukherjee's (1971) conclusion that the F_1 Ross Creek syncline continues eastward, across the Channing fault, and that F_1 - F_2 fold interference produced the F_2 plunge reversal. On the lowest conglomerate bed, minor folds (F_1 and F_2) on both sides of the basin show S-asymmetry when viewed down-plunge (Fig. 3.1; map 2, inside back cover). Stauffer and Mukherjee (1971) concluded that the S-fold on the eastern limb is a continuation of the F_1 Ross Creek syncline and thus described it as an F_1 antiformal syncline that plunges steeply to the east. An S-fold on the western limb is well exposed, has the S_2 fabric as an axial-planar foliation, and shows the correct fold asymmetry relative to the F_2 Mud Lake syncline (i.e. a north-plunging S-fold on western limb) to be interpreted as an F_2 minor fold.

Based on the above observations, the Mud Lake syncline is inferred to be an F_2 structure, consistent with the conclusion of Stauffer and Mukherjee (1971). The Mud Lake syncline is truncated to the north against the Birch View fault. There is no field evidence for this fault and it is identified on the basis of stratigraphic relationships (Stauffer and Mukherjee, 1971). Stauffer and Mukherjee (1971) concluded that the south side moved up and to the north, with respect to the north side.

3.2.4 - Relationships at the basement-cover contact

A well preserved unconformity defines the contact between the Flin Flon arc assemblage (basement) and the Missi Group (cover) in the southern portion of the study area (Fig. 3.1; Stockwell, 1960). A regolith extends up to 10 m into the volcanic rocks below this contact and consists of well-rounded volcanic fragments in a dark, chloritic matrix (Stauffer, 1990; see Plate 2.2). During this study, the basement-cover contact outcropping south of Mud Lake was mapped as vertical to steeply north dipping, and is locally overturned, dipping steeply to the south (Map 2, inside back cover). The basement-cover contact east and west of the Ross Lake fault dips moderately to the north and east, respectively (Stauffer and Mukherjee, 1971; Fig. 3.1).

Cleavages in both the basement and cover rocks were examined in a number of localities along the contact and were found to be correlative. The dominant cleavage (designated S_2) is moderately to well developed along all of the southern unconformity in both the basement and cover rocks. This cleavage is linked with the D_2 event (and is thus termed S_2) because it overprints early, east-west trending F_1 folds in the Missi Group (e.g. Ross Creek syncline). In areas along the southern basement-cover contact where the S_2 cleavage is well developed, clasts within the Missi conglomerate are flattened within the S_2 foliation plane. The intensity of flattening within this cleavage plane is variable, even where S_2 is homogeneously developed. The S_2 cleavage is overprinted by a spaced cleavage (designated S_3) which realigns conglomerate clasts and further flattens quartz and feldspar grains. No lineation has been observed within

the rocks stratigraphically above and below the unconformity.

To the south of Mud Lake, thinly-bedded ash tuff layers mapped within mafic volcanic rocks of the Flin Flon arc assemblage strike 325° and dip 67° northeast (Map 2, inside back cover). This relationship defines an angular unconformity at the basement-cover contact, suggesting that the Flin Flon arc assemblage was deformed prior to Missi Group sedimentation.

3.2.5 - Burley Lake syncline

The Burley Lake syncline, involving rocks of the Flin Flon arc assemblage, is located in the southwestern-most corner of the study area (Fig. 2.5). It was initially mapped by Stockwell (1960), who concluded that it is truncated at the unconformity. Bailes and Syme (1989) also interpreted this dominantly north-northwest-trending, isoclinal syncline as a pre-Missi Group structure that was folded into an east-west orientation by the Hidden Lake synform and truncated at the unconformity (Fig. 2.5). Poles to bedding from the north-northwest-trending segment of the fold define a cluster of data points, and not a π -girdle; as a result, the attitude for the fold axis is not known (Bailes and Syme, 1989). In contrast, Stauffer (1990) mapped in the Burley Lake syncline area and linked this fold to the east-west striking F_1 Ross Creek syncline which he identified within the Missi Group (Fig. 2.5). Stauffer (1990) proposed that the misalignment of the two axial traces at the unconformity (Fig. 2.5) is "likely to be the result of pre-Missi erosional removal of Amisk material that was undergoing early F_1 folding" and that the Missi rocks were then deposited during

continued F_1 folding, thus completing the formation of the F_1 Burley Lake syncline (Stauffer, 1990). Thomas (1992) agreed with Stauffer (1990) on the basis of his mapping in the same area.

During fieldwork conducted along the trace of the Burley Lake syncline in this study, a single foliation and a limited number of bedding measurements were observed. The S_2 foliation identified in the Ross Creek syncline area (within Missi Group; see above) was traced across the unconformity and correlated with the foliation (i.e. S_2) observed in the Burley Lake syncline area. Bedding measurements indicating a facing reversal in these mafic pillowed basalts were combined with data from Thomas (1992) to define the position of the syncline's axial trace (Fig. 3.1; Map 2, inside back cover). No minor folds related to the Burley Lake syncline were observed and, because dips of bedding could not be easily measured, the orientation of the axial plane and fold axis cannot be determined on the basis of data from this study. The S_2 foliation has an average orientation that strikes 341° and dips 40° northeast (Fig. 3.4), and therefore transects both limbs of the fold. Thus the Burley Lake syncline is interpreted to be F_1 or older.

A number of points suggest that this syncline formed prior to Missi sedimentation and is associated with a pre-Missi Group deformation event. The north-northwest striking segment of the Burley Lake syncline (to the south of the study area) is mapped as an isoclinal fold (Bailes and Syme, 1989). If it is assumed that the east-west striking segment of the Burley Lake syncline has the same isoclinal fold geometry, then it is hard to explain why the unconformity is not folded where it is

intersected by the syncline's axial trace (Fig. 3.1). Bedding within the Missi conglomerate, lying unconformably above and to the east of the syncline's axial trace, shows a constant strike of 330° (Map 2, inside back cover). Even though the position of the syncline's axial trace immediately below the unconformity is not known with certainty, bedding in the Missi Group does not vary along the entire southwestern portion of the contact, suggesting that the Missi Group is not folded.

These points suggest that the Burley Lake syncline is an early structure that predates Missi Group sedimentation and was truncated by the unconformity. This corresponds to the interpretation of Stockwell (1960) and Bailes and Syme (1989).

3.2.6 - Sepple Hill shear zone

The Sepple Hill structure is located about 250 m south of the western arm of Ross Lake (Fig. 3.1). Fedorowich et al. (1995) examined this structure and associated it with the earliest deformation event observed within the Missi Group (D_1 , this study; Table 1). The basement-cover contact along the southern and western sides of the Missi Group basin (southern region; Fig. 3.1) is mapped as a well-preserved unconformity (Stauffer and Mukherjee, 1971). At Sepple Hill, the north-south striking basement-cover contact changes in orientation and adopts an east-west strike (Fig. 3.6). Along this east-west striking segment, the volcanic rocks structurally overlie the sedimentary rocks (Plate 3.5; Fedorowich et al., 1995).

The oldest fabric observed during this study in the Sepple Hill area occurs at the unconformity and is developed within a shear zone that extends 10-20 cm into the

Figure 3.6. Map of Sepple Hill area showing the Sepple Hill shear zone. Equal area stereonet plots show D₁ shear fabric, S₂ and L₂ data.

Plate 3.5: Basement-cover contact at Sepple Hill (solid black line extending across photo). The basement-cover contact is dipping to the south and is folded by F_2 folds. Flin Flon arc assemblage (dark, pitted rocks; FFaa) is in the hanging-wall and Missi Group (light coloured rocks; Missi) is in the footwall. Graffiti on eastern-most cliff face is 3 m high and the view is to the southwest.

Plate 3.6: Photomicrograph (plane polarized light) of S_1 and S_2 cleavage from Missi Outlier (thin section plane strikes 154° and dips 32°). S_1 is defined by chlorite (Chl), muscovite (Ms) and some opaque oxides (black minerals). S_2 cleavage crenulates the S_1 and is defined mainly by opaque oxides, with minor chlorite. Width of photo is 1 mm.

Plate 3.5

Plate 3.6

Missi Group (footwall) and the volcanic rocks (hanging-wall). It consists of a generally south-dipping foliation that is defined by flattened pebbles, as well as quartz and feldspar grains (Missi Group), and volcanic fragments and amygdules (Flin Flon arc assemblage). This foliation branches away from the basement-cover contact in two localities, forming 0.5-1.5 m wide shear zones contained completely within the volcanic basement (Fig. 3.6). These early shear zones along the basement-cover contact and within the volcanic rocks show extensive chlorite with quartz-carbonate veining. Unfortunately, no kinematic indicators were observed within these shear zones in the field or in thin section during this study. A weak lineation (defined by striations) plunging moderately towards the south-southeast is developed within these shear zones (Fig. 3.6). Fedorowich et al., (1995) recognized kinematic indicators (i.e. rotated quartz amygdules observed in thin section) from within the shear zone that are consistent with northward displacement of the basement rocks over the Missi Group. The volcanic rocks in the hanging-wall to the sheared unconformity are composed of regolithic material which contains mafic volcanic and epidote fragments in a dark chloritic matrix. In the footwall rocks, a 30-50 cm thick conglomerate bed grades into pebbly sandstone. These relationships suggest that the basement-cover contact is downward-younging and therefore is overturned. Fedorowich et al. (1995) termed the sheared basement-cover contact and the shear zones within the volcanic rocks the Sepple Hill shear zone.

The shear zone fabric at the unconformity is deformed by overturned, tight to isoclinal, west-verging folds that have a mean fold axis calculated to plunge 46°

towards 123° (Fig. 3.6). These folds have an axial planar foliation (regional S_2) which is the dominant fabric in the Missi Group but only weakly to moderately developed within the Flin Flon arc assemblage. The poles to these foliation planes define a cluster, with a mean plane striking 002° and dipping 41° east (Fig. 3.6). The shear zone fabric within the volcanic rocks is deformed by similarly oriented folds. Based on these overprinting relations, the shear zone developed at the unconformity and within the volcanic rocks is designated as a D_1 structure. Within the foliation at the overturned unconformity, centimetre-scale isoclinal folds of the S_1 fabric are observed adjacent to the F_2 mesoscopic folds, and are interpreted to indicate that, in some sections, the foliation at the basement-cover contact is a composite of S_1 and S_2 . A linear fabric defined by elongated pebbles in the conglomerate was observed (plunging 30° towards 133°) and is correlated with the regional L_2 lineation (Fig. 3.6, 3.4).

At one locality in the Missi Group, the S_2 foliation is crenulated by a spaced foliation (striking 351° and dipping 74° east), which is axial planar to rare north-northwest-striking open folds. Because of the overprinting relationships, this foliation and the associated fold are designated S_3 and F_3 , respectively.

Based on the above field relations, and conclusions by Fedorowich et al. (1995), deformation events at Sepple Hill can be summarized by the following: 1) Due to the fact that the D_1 fabric is developed at an overturned section of the basement-cover contact, it is here inferred that development of a north-verging, generally east plunging F_1 fold must have predated northward thrusting of volcanic basement over

sedimentary cover sequence. The exact location of this F_1 fold is unknown based on data collected during this study. Kinematic indicators and a weakly-developed L_1 fabric within the shear zone suggest a north to north-northwest vergence for the Sepple Hill shear zone (Fedorowich et al., 1995; this study). The D_1 shear zones that splay from the basement-cover contact into the volcanic rocks divide the rocks into two panels that accommodated the northward vergence in this area; 2) D_2 deformation produced west-verging, isoclinal F_2 folds, an S_2 cleavage and a weakly developed L_2 extension lineation. The extension lineation is linked with the S_2 foliation because it lies within the mean S_2 cleavage plane (Fig. 3.6) and because relationships elsewhere in the study area associate a regionally pervasive lineation with the D_2 event; 3) Open, F_3 folds with an axial planar crenulation cleavage deformed the S_2 foliation within the Missi Group.

3.2.7 - Microscopic relationships

All of the rocks in the southern study area were metamorphosed to lower greenschist facies conditions (Digel and Gordon, 1995). In the Missi Outlier, all three foliations were observed in the field but only the S_1 and S_2 were identified in thin section. Metamorphic minerals chlorite, muscovite and actinolite define the S_1 foliation, and are overprinted by an S_2 crenulation cleavage (see Plate 3.6). The S_2 cleavage is defined predominantly by opaque minerals, which are interpreted as evidence for dissolution along the S_2 cleavage traces. Minor actinolite and chlorite are also aligned in the S_2 foliation. Alignment of metamorphic minerals in the S_1 fabric is

apparently anomalous because everywhere else in the study area, the peak metamorphic minerals are associated with the S_2 cleavage. This could suggest that the age difference between the D_1 and D_2 events is not significant, accounting for peak-metamorphic minerals defining both foliations (S_1 and S_2) in different parts of the field area. Alternatively, it could suggest that the peak metamorphic minerals have broad stability fields, such that they were stable during D_1 and D_2 .

In thin sections from the Mud Lake syncline area, only the pervasive S_2 cleavage was observed. This cleavage is defined by chlorite, muscovite and actinolite, wrapping around large grains of quartz and feldspar. Evidence for the L_2 lineation, which is weakly developed in the Mud Lake syncline area, was not observed in thin section.

In a thin section (cut transverse to the high-strain zone planar fabric and parallel with the weak L_1 fabric) from the basement-cover contact at Sepple Hill, one strong foliation was observed defined by chlorite and quartz.

3.3 - Structures in the Northern region

Within the northern region, the Missi Group was initially examined to confirm previously published structural models, before structures within the Flin Flon arc assemblage were studied. The following discussion will focus first on the Pipeline fold interference basin and the Flin Flon Creek syncline within the Missi Group, followed by the Hidden Lake synform, Club Lake structure and Railway faults within

the Flin Flon arc assemblage. Description of the structures observed in the area immediately north of Ross Lake will conclude the overview of the northern study area. The microscopic relationships from the sedimentary and volcanic rocks will be presented at the ends of the respective sections.

3.3.1 - Pipeline fold interference basin

The Pipeline structure is located just east of Little Cliff Lake and is outlined by a conglomerate horizon (Fig. 2.5; Ambrose, 1936a; Stockwell, 1960; Stauffer and Mukherjee, 1971; Bailes and Syme, 1989). A pervasive cleavage, correlated regionally with the S_2 , is axial planar to the north-south trending Pipeline syncline and overprints a northwest-southeast striking F_1 fold (Fig. 2.5; Flin Flon Creek syncline) located in the core of the F_2 syncline (Stauffer and Mukherjee, 1971). Based on these relationships, the Pipeline syncline is designated as an F_2 structure and fold interference between the F_1 and F_2 folds produced the Pipeline structural basin. D_2 structures which control the dominant geometry of this interference basin will be discussed first, followed by D_1 and D_3 structures.

3.3.1.1 - D_2 deformation

As mentioned above, the Pipeline syncline controls the outcrop pattern of the conglomerate horizon (Stauffer and Mukherjee, 1971). The northern fold closure has an overturned eastern limb that dips 60° - 80° east and a western limb that dips 30° southeast (Fig. 3.7; Map 1, inside back cover; Stauffer and Mukherjee, 1971). Based

Figure 3.7. Pipeline syncline with equal area stereonet plots showing S_0 data from northern and southern closures. Cross sections show a northward view and demonstrate F_1 and F_2 folds.

on this data the Pipeline syncline is described as an overturned, tight west-verging fold (Fig. 3.7; Stauffer and Mukherjee, 1971). The northern fold hinge was calculated to plunge 29° towards 133° (Fig. 3.3) and the calculated axial plane strikes 005° and dips 33° east. The pervasive foliation, with a mean orientation striking 002° and dipping 29° east (Fig. 3.3), overprints an early generation of folds in the core of the Pipeline syncline, is co-planar with the calculated axial plane of the Pipeline syncline and is therefore designated as an S_2 axial planar cleavage (Fig. 3.1, 3.4; Stauffer and Mukherjee, 1971).

In the southern-most portion of the basin, the conglomerate horizon is not exposed and the fold pattern is defined by bedding traces within the pebbly sandstone unit (Fig. 3.7). The fold hinge is calculated to plunge 41° towards 120° , the axial plane is calculated to strike 001° and dip 45° east, and the S_2 foliation has the same attitude as in the northern portion of the fold (Fig. 3.3, 3.4). The S_2 cleavage is not axial planar to this southern closure and overprints both fold limbs (Map 1, inside back pocket). Therefore, it can be inferred that the southern closure is actually an F_1 fold. This observation is in contrast with the interpretation by Stauffer and Mukherjee (1971), who suggest that this fold is the southern closure of the F_2 Pipeline syncline. The southern closure to the F_2 Pipeline syncline must occur farther to the west and therefore cannot be mapped because it is truncated by the Ross Lake fault.

Conglomerate clasts within this area are observed to form prolate, cigar-shaped ellipsoids with aspect ratios of up to 7:1 (Plate 3.7; Stauffer and Mukherjee, 1971). The linear fabric plunges 28° towards 130° (Fig. 3.4), within the S_2 foliation plane,

Plate 3.7: L_2 fabric developed within the conglomerate on the northwestern limb of the Pipeline syncline. All clasts form prolate, cigar-shaped ellipsoids. Pen is 15 cm in length and is aligned in the L_2 fabric (plunging 30° towards 130°).

Plate 3.8: S_2 and S_3 overprinting relations in sandstone (unit 3; Stauffer, 1990) from the southeast corner of the Pipeline interference basin. S_2 is the pervasive foliation deformed by the spaced S_3 cleavage. Pen is aligned in the S_3 plane and is 15 cm in length. View is towards the southeast.

Plate 3.7

Plate 3.8

and is defined by peak metamorphic minerals (therefore designated L_2 ; Fig. 3.4; Stauffer and Mukherjee, 1971).

3.3.1.2 - D_1 deformation

On the basis of reversals of younging directions (cross-bedding) in sandstones, three map-scale folds have been inferred to lie within the Pipeline interference basin (Fig. 3.1). These folds are designated as F_1 structures because they are transected by the S_2 foliation (Fig. 3.4). In this area, there is no field evidence for a foliation pre-dating the pervasive S_2 fabric.

The F_1 folds in the central part of the Pipeline syncline are closed to tight, upright, and have hinges that are calculated to plunge 23° towards 128° . On the eastern side of the F_2 synclinal axial surface trace, the F_1 folds are overturned and deflect the conglomerate horizon in the southeast corner of the basin (Fig. 3.7). As a result of F_2 overprinting, the F_1 folds in the southeast corner have become a series of antiformal synclines and synformal anticlines. These F_1 folds are overturned and isoclinal, and have axial planes dipping steeply to the northeast and fold hinges calculated to plunge 41° towards 115° . The southernmost fold in the Pipeline syncline was previously thought to be an F_2 closure (Fig. 2.5; Stauffer and Mukherjee, 1971). However, the S_2 foliation is not axial planar to the fold so this structure is here reinterpreted as an F_1 antiformal syncline. Incorrect fold asymmetry in the southeastern corner of the Pipeline structural basin (Z-asymmetry when viewed down plunge) relative to the southeast plunging F_2 Pipeline syncline provides further

evidence that these folds are F_1 structures.

To determine the orientation of the F_1 folds prior to F_2 folding, F_2 deformation must be removed by completing rotations about a plunging pole (F_2 axis: plunges 29° towards 133°). This F_2 fold axis is not presumed to be the unique pole of rotation for F_2 deformation, but was used for the purpose of this exercise. Results show that the F_1 folds had generally south-dipping axial planes (approximately striking $070-085^\circ$ and dipping $40-50^\circ$ south) prior to the onset of F_2 deformation.

On the west side of the F_2 syncline's axial trace, outcrop exposure is very poor. Given that the conglomerate horizon on this western limb is not folded, it is suggested that the F_1 axial traces are folded parallel to bedding and adopt a southwest strike (Fig. 3.1). These F_1 folds are inferred to be truncated against the Ross Lake fault.

3.3.1.3 - D_3 deformation

To the north of the Pipeline syncline (on the north shore of Flin Flon Creek, Fig. 3.1) there is an isolated fold of decametre scale that deforms the S_2 . This structure is an open, upright fold that has an axial plane striking 311° and dipping 70° northeast, which corresponds to the average orientation of the S_3 foliation (Fig. 3.5). These two relationships suggest that this particular fold is an F_3 structure, the only mapped expression of F_3 folding in the Pipeline area. Throughout the Pipeline area, a second foliation (designated S_3) is observed to overprint S_2 and re-flatten pebbles, and quartz and feldspar grains (Fig. 3.5; see Plate 3.8). Within the conglomerate horizon

approximately 100-200 m north of Little Cliff Lake (Fig. 3.1), the S_3 foliation is more intensely developed. The S_2 cleavage is deflected and conglomerate clasts are realigned into the northwest-striking, steeply-northeast dipping S_3 cleavage plane. The linear fabric in this area does not show any variation in orientation with respect to overprinting S_3 deformation.

3.3.1.4 - Summary

In summary, three fold generations (F_1 , F_2 , and F_3) and two cleavage generations (S_2 and S_3) were observed in the Pipeline interference basin. On the eastern limb of the F_2 Pipeline syncline the F_1 folds are overturned and form a set of antiformal synclines and synformal anticlines. The fold closure in the south of the basin is reinterpreted as an F_1 fold. The generally south-dipping F_1 axial surfaces were overprinted by the shallowly east-dipping F_2 axial surface, producing a Type-II fold interference pattern (Ramsay, 1967). Figure 3.8 shows a three dimensional view of the Pipeline interference basin. The fold hinges of the F_1 folds in the southeast corner of the basin (see Fig. 3.7) plunge moderately towards the southeast at surface (horizontal datum) and then change at depth, to plunge to the northwest (Fig. 3.8). This geometry is due to deformation related to the F_2 Pipeline syncline. When the effects of F_2 folding are removed, it appears that the F_1 folds initially had moderately south-dipping axial surfaces. F_3 folds are rare but the associated S_3 cleavage is moderately developed.

Figure 3.8. Schematic three dimensional view (from within the subsurface, looking northwestward) of the Pipeline interference basin. Conglomerate unit (tanned colour) is truncated at the Ross Lake fault. One block on the horizontal datum is 500 m² and the structural contours on the conglomerate unit and the Ross Lake fault are spaced 75 and 300 m apart, respectively.

3.3.2 - Flin Flon Creek syncline

The Flin Flon Creek syncline has been mapped by Ambrose (1936a), Stockwell (1960), Stauffer and Mukherjee (1971). It is an east-west trending, northerly overturned structure located in the northern portion of the study area (Fig. 2.5). Ambrose (1936a) proposed that the Flin Flon Creek syncline is an asymmetric footwall syncline formed as a result of northward thrust movement on the Club Lake fault (Fig. 2.5). These relationships will be discussed below in section 3.3.5 (Club Lake structure). Stauffer and Mukherjee (1971) describe the fold as having an east-west striking axial plane, with a fold hinge calculated to plunge 30° towards 110° . These authors also concluded that the Flin Flon Creek syncline continues across the Pipeline interference basin as an F_1 structure (i.e. on the eastern side of the Ross Lake fault (Fig. 2.5).

Detailed mapping was carried out in the Flin Flon Creek area during this study. The northern limb of the Flin Flon Creek syncline strikes 090° and dips 30° - 65° south, and the southern limb strikes 320° and dips 50° - 80° northeast. Portions of the southern limb are overturned steeply to the southwest (Map 1, inside back cover; Stockwell, 1960; Stauffer and Mukherjee, 1971). The axial surface dips approximately 60° to the south, and the fold hinge is calculated to plunge 32° towards 122° (Fig. 3.1). This fold geometry matches that observed by Stauffer and Mukherjee (1971) and suggests that fold vergence is towards the north to northeast. There is no field evidence for a cleavage associated with this fold. The dominant fabric in the area has a mean orientation that strikes 022° and dips 27° east, and is designated as

the S_2 cleavage because it transects both limbs of the fold (Fig. 3.4; Stauffer and Mukherjee, 1971). Another, more weakly developed fabric (designated S_3) with a mean orientation striking 320° and dipping 75° northeast, overprints the S_2 cleavage (Fig. 3.5). A lineation defined by the elongation of clasts shows a constant orientation that plunges 20° towards 121° and lies within the S_2 axial plane (Fig. 3.4). This is parallel with the mean lineation (plunging 30° towards 132°) which Stauffer and Mukherjee (1971) described as L_2 .

3.3.3 - Microscopic relationships in the Missi Group

Within the Pipeline interference basin, both the S_2 and S_3 cleavages were observed in sections cut transverse to the respective foliations. Peak metamorphic minerals consisting of chlorite, actinolite, muscovite, and biotite, together with inequant quartz and feldspar grains, define the pervasive S_2 cleavage (Ambrose, 1936b; Stauffer and Mukherjee, 1971). The S_3 cleavage is a spaced foliation that forms rare, 0.5-1 mm wide zones defined by new mineral growth of muscovite and epidote, with minor chlorite. The spaced S_3 cleavage domains realign minerals forming the dominant S_2 fabric (Plate 3.9). Evidence for the extension lineation (L_2) is observed in sections cut perpendicular to the elongation direction (within the Y-Z plane relative to the S_2 foliation). In these sections, there is only a weakly to moderately developed S_2 fabric and the quartz and feldspar crystals are relatively equant in shape. This relationship suggests that alignment of minerals in sections cut transverse to S_2 and parallel to L_2 is primarily the result of constriction, with only a

Plate 3.9: Photomicrograph (cross-polarized light) of S_2 and S_3 fabric in sandstone (unit 3; Stauffer, 1990) from north of Little Cliff Lake (thin section is cut transverse to the S_3 cleavage and parallel to the L_2 fabric). Muscovite (Ms) is the dominant mineral defining the S_2 , while increased muscovite defines the S_3 . Some of the quartz (Qtz) grains show undulose extinction. Width of photo is 2 mm.

Plate 3.10: Photomicrograph (cross-polarized light) of a sandstone (unit 3; Stauffer, 1990) from the Flin Flon Creek syncline area (the thin section is cut transverse to the S_2 and parallel to the L_2). ' S_2 ' is the only observable fabric and is defined by muscovite (Ms) and flattened quartz (Qtz). Width of photo is 2 mm.

Plate 3.11: Photomicrograph (cross-polarized light) of a sandstone from the Flin Flon Creek syncline area (thin section is from the same rock as Plate 3.10 and is cut transverse to the L_2). The muscovite (Ms) is not aligned and the quartz (Qtz) forms relatively equant crystal shapes. The absence of a flattening fabric in this plate demonstrates that the fabric depicted in Plate 3.10 is due to elongation (L_2), instead of flattening (S_2 ; therefore $L > S$ tectonites). This relationship is due to the orientation of this section (transverse to L_2). Width of photo is 2 mm.

Plate 3.9

Plate 3.10

Plate 3.11

minor component of flattening in the S_2 plane. Therefore, it can be concluded that these rocks underwent prolate strain and are $L > S$ tectonites.

Thin sections from the Flin Flon Creek syncline (cut transverse to the S_2 and parallel with the L_2) show a well developed, pervasive S_2 fabric defined by chlorite, muscovite and biotite, as well as elongated quartz and feldspar (see Plate.3.10; Ambrose, 1936b; Stauffer and Mukherjee, 1971). Thin sections cut transverse to the L_2 show a weak to moderate S_2 fabric and roughly equant quartz and feldspar crystals (see Plate 3.11). The variation in S_2 cleavage intensity between these two perpendicularly oriented thin sections suggests again that D_2 mineral alignment is not simply the result of flattening but instead is largely due to constriction. Therefore, it can be concluded that these rocks experienced some degree of flattening but are $L > S$ tectonites, produced by prolate strain.

3.3.4 - Hidden Lake synform

The Hidden Lake synform (Fig. 2.5) is defined by flow contacts, tuff layers, and pillow facing directions (Stockwell, 1960; Bailes and Syme, 1989). Bailes and Syme (1989) mapped this synform and describe it as having an axial planar schistosity that strikes 341° and dips 80° east, and a hinge that plunges 46° towards 133° . Bailes and Syme (1989) assigned the Hidden Lake synform to a folding event that apparently was not developed in the sedimentary rocks of the Missi Group (Table 1).

The Hidden Lake synform was examined during this study. Bedding on the western limb dips 30° - 40° southeast, whereas it dips 65° - 80° southwest on the eastern

limb (Map 1, inside back cover; Bailes and Syme, 1989), with some beds locally overturned (dipping 75-85° northeast) in this eastern portion of the fold. The poles to bedding planes define a fold hinge plunging 41° towards 146° (Fig. 3.3).

Two regional foliations are observed within the volcanic rocks of the Hidden Lake synform (Bailes and Syme, 1989). The first is a northeast-striking, shallowly to moderately southeast-dipping foliation that is subparallel to S_2 in the Missi Group sedimentary rocks (Fig. 3.4). The foliation in the volcanic rocks has the same penetrative, syn-metamorphic nature as S_2 in the Missi Group, and they are thus correlated. It is important to note that this foliation maintains a roughly constant strike across the core of the Hidden Lake synform (Fig. 3.4). The second regional foliation in the volcanic rocks is a northwest-striking, moderately to steeply northeast-dipping spaced cleavage. This fabric has a mean orientation striking 327° and dipping 73° northeast, parallel to S_3 in the Missi rocks (Fig. 3.5). It overprints the penetrative S_2 foliation in the basalts (Plate 3.12) and is thus correlated with S_3 in the Missi Group. Within the Hidden Lake basalts, there are a series of high-strain zones that are 0.2-5 m thick, strike parallel to the mean S_3 cleavage and are marked by an increase in chlorite. These zones overprint the S_2 cleavage and have been designated as S_3 high-strain zones.

Elongated quartz amygdules, pillows and clasts in volcanoclastic beds define a well-developed stretching lineation with a mean orientation plunging 28° towards 134° (Fig. 3.4; Plate 3.13). This lineation is parallel to L_2 in the rocks of the Missi Group and they are interpreted to be correlative (Bailes and Syme, 1989).

Plate 3.12: S_2 and F_3 relations from the Hidden Lake synform, south of the South Railway fault. The S_2 pervasive cleavage is folded about an upright, open F_3 fold. Scale card is 8 cm in length and view is to the southeast.

Plate 3.13: Pillow basalts from the Hidden Lake syncline area elongated in the lineation (L_2 : plunging 30° towards 130°). Scale card is 8 cm in length.

Plate 3.12

Plate 3.13

The Hidden Lake synform is interpreted as an early F_2 fold, predating development of S_2 . This conclusion is based largely on evidence that is presented in the following sections.

Missi rocks in unconformable contact with the volcanic basement have been found in two outliers on the eastern limb of the Hidden Lake synform (Fig. 3.1; Map 1; inside back cover). The smaller outlier is 10 m in diameter and consists of conglomerate and sandstone overlying regolith (locality 1, Fig. 3.1). The second outlier, here designated the Missi Wedge, is found directly south of locality 1 (Fig. 3.1) and has the form of a wedge-shaped, fault-bounded basin, with the Missi rocks unconformably overlying the Hidden Lake basalts on the northwest and southeast ends, and in fault contact along the northwest-trending eastern and western margins (Stockwell, 1960; Bailes and Syme, 1989). Pebbles within the conglomerate above the unconformity are elongated parallel to the dominant L_2 lineation, and are variably flattened within S_2 or S_3 cleavage planes. Most pebbles are flattened in the S_2 plane but are realigned and further flattened in S_3 high-strain zones.

3.3.5 - Relation between the basement-cover contact and Club Lake structure

The structure defining the basement-cover contact (i.e., Club Lake 'fault') in the northern part of the study area (Fig. 2.3, 3.1) has been described in previous studies (Bruce, 1918; Ambrose, 1936a; Stockwell, 1960; Stauffer and Mukherjee, 1971; Bailes and Syme, 1989). Ambrose (1936a), along with Bruce (1918), initially mapped it as a north-verging thrust fault (Creighton Creek fault) that juxtaposes

volcanic rocks over sedimentary rocks. Ambrose (1936a) extended the Club Lake 'fault' from the western end of the basement-cover contact in Saskatchewan, where it is cut by a north-northwest trending fault, to the position where the contact is cut by the Ross Lake fault in Manitoba (Fig. 2.3; Map 1, inside back cover). Stauffer and Mukherjee (1971) describe how the fault zone is brecciated, intensely fractured and veined, chloritized, and, in some localities, shows volcanic rocks tectonically interlayered with sedimentary rocks. Stauffer and Mukherjee (1971) did not distinguish between the relative ages of the faults within the study area and associated them all with the last episode of northwesterly-directed thrusting (D_4 , this study). By assuming these kinematics, Stauffer and Mukherjee (1971) proposed an approximate net slip of 1067-1820 m for the fault.

During this study, mapping along the basement-cover contact was started at the northeastern tip of Club Lake and continued eastward, into Manitoba, until reaching Little Cliff Lake (Fig. 2.3; Map 1, inside back cover; Bruce, 1918; Ambrose, 1936a). For the purpose of this discussion, the Club Lake fault is renamed the Club Lake structure and is divided into two sections that generally coincide with the provincial border. The western (i.e. Saskatchewan) and eastern (i.e. Manitoba) sections will be discussed separately.

3.3.5.1 - Western section of the Club Lake structure

At the northeastern tip of Club Lake, the contact between the cover (Missi Group) and basement (Flin Flon arc assemblage) is marked by a 30-40 cm thick zone

of strongly foliated chloritized mafic volcanic rocks with veins of quartz and carbonate. The hanging-wall consists of mafic volcanic rocks with thin rhyolite flows and the footwall is composed of a coarse-grained feldspar-porphyry with rotated porphyroclasts which indicate that the hanging-wall block moved relatively northward. Missi Group sandstone (footwall) is not exposed at this locality, but is observed 40 m along strike to the northeast and occurs 2-3 m north of an outcrop of volcanic rock. The planar fabric that lies in the shear zone strikes 046° and dips 24° southeast. The shear fabric in the porphyry extends 30-40 cm below the contact with the mafic volcanic rocks and is defined by flattened feldspar phenocrysts. The elongate feldspar porphyroclasts in the shear zone define a linear fabric that plunges 21° towards 129° . The porphyry in the footwall to the Club Lake structure is too small to be shown on Map 1 (inside back cover).

An outcrop of Boundary Intrusion that is located 400 m east-northeast of the northeastern tip of Club Lake (Map 1, inside back cover) has a strong planar fabric striking 055° and dipping 40° southeast and a linear fabric defined by elongated amphiboles plunging 32° towards 127° . This fabric is not confined to a specific zone, but instead forms a pervasive foliation over the entire outcrop. This fabric is significant because throughout this area, Boundary Intrusions are only weakly foliated (e.g., S_2 and S_3 , as identified in the Flin Flon Creek syncline area), which suggests that this strongly developed northeast striking fabric is related to deformation along the Club Lake structure. The Club Lake structure is not exposed but is inferred to occur 30-50 m to the north of this locality (Map 1, inside back cover). No evidence

of an S_2 cleavage was observed at this outcrop. A weak northwest-striking cleavage was observed to cross-cut the strong fabric and is attributed to S_3 (as identified within the Missi Group). Based on these relationships, it can be inferred that deformation related to the Club Lake structure postdates emplacement of the Boundary Intrusions ($1842 \pm 3/_{-3}$ Ma; Heaman et al., 1992).

Slightly west of the provincial border where the Club Lake structure crosses Flin Flon Creek (Map 1, inside back cover), further evidence for a zone of deformation at the basement-cover contact can be observed. Along the northern side of an outcrop of mafic volcanic rock, an increase in chlorite growth and flattening of amygdules is observed over a distance of 1.5 m. A strong ductile fabric is developed at the northern base of this outcrop. This zone of high strain strikes 045° and dips 29° southeast and shows a linear fabric (stretched amygdules) plunging 29° towards 119° . Kinematic indicators were not observed within the shear zone and the actual basement-cover contact is not exposed. The Missi Group occurs 1 m to the north of this high-strain zone and does not show a similarly developed fabric. To the north within the Missi Group, and to the south within the Flin Flon arc assemblage, the S_2 cleavage shows a constant strike of 020° but it was not observed within the high-strain zone (Map 1; inside back pocket). The fabric documented in the high-strain zone (i.e. developed only at the basement-cover contact) is interpreted as S_1 because the S_2 cleavage is oblique to this fabric and maintains a constant strike in the area.

3.3.5.2 - Summary

The evidence given above from the three localities along the western portion of the Club Lake structure indicate that there is a shear zone developed along the basement-cover contact. Based on the limited kinematic indicators for reverse movement, and the fact that the zone appears to be overprinted by S_2 , the Club Lake structure is concluded to have originally formed during the D_1 event as a thrust juxtaposing volcanic basement rocks over the sedimentary cover sequence. The retrograde mineral assemblage (chlorite, quartz and carbonate) defining the shear zone suggests that the fabric is actually a composite fabric, consisting of multiple foliations (S_{1+n}). At the Boundary Intrusion locality described above, the intense fabric is inferred to be related to deformation along the Club Lake structure. There is not enough outcrop exposure in the area to determine whether the contacts of the Boundary Intrusion are offset where it crosses the basement-cover contact.

3.3.5.3 - Eastern section of the Club Lake structure

The basement-cover contact in Manitoba is exposed north of the Hidden Lake basalts on a steeply north-dipping cliff face (intersection of Flin Flon Lake fault with Club Lake structure; Fig. 3.1; Map 1, inside back pocket). Along this eastern section, the basement-cover contact varies in character from being a thrust fault with preserved regolith in the hanging-wall volcanic rocks, to being an intact, but folded, unconformity.

The basement-cover contact is exposed at the base of a cliff above the southern

shore of Flin Flon Creek. A sharp contact shows volcanic rocks overlying sedimentary rocks of the Missi Group. A moderately-developed planar fabric parallel to the contact (striking 045° and dipping 42° southeast) occurs mostly within the volcanic rocks and is parallel to the principal planes of flattened pillows. The S_2 and S_3 cleavages were not observed at this locality. A linear fabric (defined by elongated quartz and feldspar grains) plunges 32° towards 134° on the surface of the basement-cover contact.

At a locality fifty metres to the east, the basement-cover contact is folded by several generations of structures. These relationships are shown in a west-southwest - east-northeast striking cross-section (Fig. 3.9-B). The hanging-wall, immediately above the faulted basement-cover contact, is regolithic material composed of rounded epidote fragments in a dark purple, chlorite- and hematite-rich matrix (Plate 3.14; Holland et al., 1989). The regolithic material is overlain by Hidden Lake basalt (mafic pillowed flows), which continues to the south (Bailes and Syme, 1989). Below the basement-cover contact, the footwall rocks consist of Missi Group sandstone (unit 3; Stauffer, 1990). Thus the basement-cover contact is an overturned (i.e. downward-facing) unconformity.

At this outcrop (Fig. 3.9-B), a weakly developed foliation is observed parallel to the basement-cover contact (striking 050° and dipping 45° southeast; Plate 3.15). It extends only 10-20 cm into both the hanging-wall and the footwall rocks and is defined by flattened pods of epidote (in regolith, volcanic rocks) and flattened quartz and feldspar grains with minor quartz vein development (Missi Group). This weakly-

Figure 3.9. (A) Map view of the Club Lake structure showing locations of folds and cross sections. (B) West-southwest -east-southeast cross section shows northward view. (C) North-northwest - south-southeast cross section shows a westward view. F_1 fold asymmetry indicates an anticline to the south and a syncline to the north.

Plate 3.14: Regolithic material composed of rounded epidote fragments in a dark purple, chlorite- and hematite-rich matrix. Photo is located in the hanging-wall, structurally above the Club Lake structure depicted in Plate 3.15, and demonstrates how the basement-cover contact is downward-facing (overturned; see Fig. 3.9-B for exact location). Pen is 15 cm in length and view is to the west.

Plate 3.15: Club Lake structure (defined by dashed line) north of Hidden Lake synform (see Figure 3.9-B for exact location). Flin Flon arc assemblage (labelled Amisk) is in the hanging-wall and Missi Group sandstone (labelled Missi) is in the footwall. Light-coloured epidosite pods define the regolith in the Flin Flon arc assemblage. Width of photo is 2 m and view is to the south.

Plate 3.14

Plate 3.15

developed fabric is complexly folded, parallel with the basement-cover contact (Fig. 3.9-B; Plate 3.16). No kinematic indicators were observed within the fabric along this section of the basement-cover contact. A cleavage striking 010-020° and dipping 30-35° east can be traced from the Hidden Lake basalts, northward across the basement-cover contact into the Missi Group, with no strike variation. This cleavage is designated S_2 because it is parallel to the S_2 identified within the Flin Flon Creek syncline area to the north (Fig. 3.4). The fabric parallel to basement-cover contact is designated as S_1 because of the overprinting relationships shown by S_2 . The S_3 cleavage that was identified in the Flin Flon Creek syncline area, and to the south within the Hidden Lake basalts, was not observed at this outcrop. A linear fabric defined by a mineral elongation (quartz and feldspar grains) is developed along the folded basement-cover contact and has a mean attitude of 30° plunging towards 120°. As this lineation is parallel to the regional linear fabric (Fig. 3.4), and also because it is not folded with the basement-cover contact or the associated shear fabric, it is concluded that this linear fabric is L_2 .

The S_2 cleavage was used to constrain the age of the folds developed at this locality and either cross-cuts both fold limbs of minor folds (F_1) or is axial planar to them (F_2 ; Fig. 3.9-B). These relationships indicate that the folds at this outcrop are dominantly F_1 , with two F_2 folds located to the west (Fig. 3.9-B). Only a limited number of fold axes were obtained for these folds (Fig. 3.9-B). A vertical cross-section shows that the axial planes of these F_1 folds are parallel to the mean attitude of the fabric developed along the basement-cover contact (Fig. 3.9-C). These F_1 folds

Plate 3.16: Folded Club Lake structure (highlighted by dashed lines) north of Hidden Lake synform (see Figure 3.9-B for exact location of Plate). Missi Group sandstone (lighter coloured rocks labelled Missi) is folded and surrounded by Flin Flon arc assemblage (labelled Amisk). Rock hammer is 30 cm in length and view is to the southwest.

Plate 3.17: F_3 folding (Z-asymmetry) of the unconformity north of the Hidden Lake synform (see Figure 3.9-A for exact location). Missi sandstones (labelled Missi) are the lighter coloured rock. Hidden Lake basalts are the darker coloured rock (labelled Amisk) and regolith is shown by light coloured blocks (epidosite 'clasts'). Basement-cover contact dips steeply to the northeast. Pen is 15 cm in length and view is to the southwest.

Plate 3.16

Plate 3.17

most likely formed during progressive D_1 deformation along the basement-cover contact, producing folds of the S_1 fabric and a rotation of the F_1 axial surfaces into an orientation parallel to the mean S_1 fabric. The asymmetry of the F_1 folds suggests an anticline (here named the Ross Lake anticline) to the south and a syncline (Flin Flon Creek syncline) to the north (Fig. 3.9; NNW-SSE cross-section). Southeast plunging F_2 Z-folds (which appear as S-folds in Fig. 3.9-B) with northeast-striking limbs, combined with the downward younging direction at the basement-cover contact, suggest an F_2 synformal anticline to the east (Hidden Lake synform).

Between the area of Figure 3.9-B and the enlarged area on Figure 3.9-A, the basement-cover contact has a moderately to strongly developed parallel ductile fabric. This fabric varies from striking 075° and dipping 40° south to striking 110° and dipping 42° southeast, just to the west of the enlarged area on Figure 3.9-A. Typically, the fabric extends 0.2-0.75 m into the volcanic rocks (flattened epidote pods and increased chlorite content) and 0.2-0.5 m into the sedimentary rocks (flattened quartz and feldspar grains). Within the foliation developed at the basement-cover contact, C-S fabric relationships (Berthe et al., 1979) indicate that the hanging-wall moved northward over the footwall, consistent with a thrust fault interpretation.

Slightly to the west of the Ross Lake fault, the basement-cover contact is folded, showing both S- and Z-asymmetry (enlarged area, Fig. 3.9-A). In this area, the shallowly east- to southeast- dipping pervasive fabric (parallel to S_2 in the Flin Flon Creek syncline and Hidden Lake synform areas) is used to determine the relative age of the various fold generations. Within the enlarged area shown in Figure 3.9-A,

there is a decametre-scale S-fold (fold hinge calculated to plunge 32° towards 128°) with a Z-fold on its eastern limb. The S_2 cleavage (mean orientation: striking 340° and dipping 37° northeast) is axial planar to the S-fold, which is thus interpreted as an F_2 structure. Interpretation of the smaller Z-fold on the eastern limb is difficult because the S_2 cleavage is not developed. A spaced foliation (striking 310° and dipping 84° northeast) matching the orientation and character of S_3 is axial planar to this fold (see Plate 3.17). This cleavage is designated S_3 and the Z-fold is labelled F_3 . This section of the basement-cover contact shows a well-preserved regolith extending 1-2 m to the southwest into volcanic rocks (see Plate 3.17). The Missi Group is in unconformable contact and consists of pebbly sandstone that grades northeastward into sandstone. These relationships demonstrate that the basement-cover contact is here unsheared, with no S_1 foliation developed.

The basement-cover contact continues to the southeast (striking 130° and dipping 70° southwest) and is folded into an decametre-scale antiformal, isoclinal S-fold (measured fold axis plunging moderately towards 145°) that has the S_2 foliation (striking 342° and dipping 40° northeast) as an axial planar cleavage (i.e. F_2 fold). The basement-cover contact is overturned (i.e. downward-facing) because there is regolith in the volcanic rocks of the hanging-wall and a thin bed of conglomerate in the sedimentary rocks in the footwall. No foliation that predates the S_2 is developed parallel to the contact. A linear fabric measured in the rocks adjacent to the contact plunges 29° towards 141° .

To the east of this locality the basement-cover contact is upright (striking 320°

and dipping 70-80° northeast) and is folded by two folds. The larger of the two is a metre to decametre-scale Z-fold (labelled F_1 Z-fold on Fig. 3.9-A) that is overprinted by the S_2 cleavage (therefore designated F_1) and has a measured fold axis plunging 12° towards 119°. On the southwestern limb of this F_1 fold, a small S-fold (measured axial plane striking 300° dipping 80° northeast and fold axis plunging 39° towards 131°) is developed that folds the S_2 cleavage (and is hence designated F_3). There is neither regolith, conglomerate nor a foliation present along the folded basement-cover contact in this area.

All the folds within the enlarged area on Figure 3.9-A plunge to the southeast and are found along a portion of the contact that generally dips steeply to the northeast as a result of folding related to the Hidden Lake synform. Based on the downward-younging nature of the unconformity, the F_1 Z-fold asymmetry suggests an F_1 anticline to the south (here named the Ross Lake anticline) and the F_2 S-fold asymmetry suggests an F_2 synformal anticline to the west (Hidden Lake synform). S_2 is deformed into both F_3 Z- and S-folds that are not correlated with any macroscopic structures.

The basement-cover contact continues to the southeast of this folded area with a mean attitude striking 315° and dipping 62° northeast. There is a strongly-developed planar fabric that extends up to 1 m into both the basement and cover rocks. The contact continues southeastward until it is truncated against the Ross Lake fault in Little Cliff Lake (Fig. 3.1).

Recently, Missi Group sandstones have been intersected structurally beneath

the Hidden Lake basalts in several diamond drill holes collared within the Hidden Lake synform (Fig. 3.10-A, -B; T. Baumgartner, D. Price, and J. Pickell, pers. comm., 1995). At locality 2 (Fig. 3.1), the basement-cover contact was encountered at a depth of 2100 m (Fig 3.10). Other drill hole information suggests that the basement-cover contact dips moderately to the south or southeast, consistent with the dip measured at surface along the east-west segment of the Club Lake structure (Fig. 3.11). The implications of these drill holes for the geometry and nature of the Club Lake structure are discussed below.

3.3.5.4 - Summary

The evidence from the localities along the eastern Manitoba portion of the Club Lake structure indicates that the basement-cover contact is a thrust fault, developed on the overturned limb of a north-verging F_1 anticline. Where the basement-cover contact is exposed as a well-preserved unconformity, the thrust fault is inferred to branch away from the basement-cover contact and juxtapose Missi Group on Missi Group. Almost the entire portion of the basement-cover contact shows an S_1 foliation, extending up to 0.75 m into either the volcanic or sedimentary rocks. This fabric, when combined with kinematic indicators observed in this study (C/S fabric relationships) and by Fedorowich et al. (1995; C/S fabric relationships, rotated quartz amygdules and clinozoisite porphyroblasts), indicates that the volcanic basement (hanging-wall) was thrust northwards, over the sedimentary cover sequence (footwall), along the basement-cover contact (i.e. Club Lake structure).

Figure 3.10. (A) Detailed map of Hidden Lake synform; three schematic cross sections incorporating drill hole results (B, C) and facing directions along the basement-cover contact (D).

Figure 3.11. Three dimensional view (from within the subsurface, looking northeastward) of the Club Lake structure and Railway faults. Four drill holes collared within the core of the Hidden Lake synform show the depths to the Club Lake structure (basement-cover contact). All distances are in metres; one square on horizontal datum surface is 500 m^2 and the structural contours on the Club Lake structure are spaced 300 m apart .

In Manitoba, the mean attitude of the penetrative linear fabric developed in rocks adjacent to the basement-cover contact plunges 33° towards 125° (parallel to the regional L_2 ; Fig. 3.4), whereas the calculated fold axis from the folded basement-cover contact plunges 29° towards 130° . These two linear features are also parallel to the axis of the Hidden Lake synform (plunging 41° towards 147°). The curved Club Lake structure is inferred to be an F_2 fold primarily based on the geometry of the overturned eastern limb. The lineation developed in the rocks adjacent to the basement-cover contact is inferred to be an L_2 fabric because it is parallel to the regional L_2 .

The presence of a preserved unconformity and regolith at the base of the two Missi outliers in the eastern limb of the Hidden Lake synform, as well as along the Club Lake structure, suggests that the basement-cover contact does not project significantly above the current erosion surface, at least on the eastern limb of the Hidden Lake synform (Fig. 3.10-D). Also, the reversals in stratigraphic facing directions between these two outliers and at the Club Lake structure define an overturned, north-verging anticline, here named the Ross Lake anticline (Fig. 3.10-D). Although the inferred axial trace of the map-scale anticline (Ross Lake anticline) is shown on Figure 3.1, field mapping within the basalts failed to discover indicators of younging direction that confirm or deny the existence of this inferred F_1 structure.

3.3.6 - Railway faults

The South Railway and the Railway faults are located within the core of the

Hidden Lake synform and are the most prominent of a set of faults that parallel the trace of the Club Lake structure (Fig. 2.5; Stockwell, 1960; Bailes and Syme, 1989; Thomas, 1992). Bailes and Syme (1989) describe the Railway and South Railway faults as curved structures that are truncated by the Ross Lake fault in the east, and suggest that they may join to become one single fault north of the Flin Flon mine horizon. They describe the South Railway fault as a 3-4 m wide schistose zone that dips moderately to the east and south on the western and central sections (respectively), and moderately to the east on the eastern sections (Bailes and Syme, 1989). The axial trace of the Hidden Lake synform crosses both faults with no offset, which constrains timing of thrusting along these faults to predate development of the Hidden Lake synform (Fig. 2.5; Bailes and Syme, 1989). Fedorowich et al. (1995) examined the Railway structures and also associated them with the earliest deformation observed in both the Flin Flon arc assemblage and the Missi Group (Table 1). They identified kinematic indicators that suggest thrusting of hanging-wall rocks northward over the footwall rocks (Fedorowich et al., 1995). The Catherine and Flin Flon Lake faults are two other faults that show this same curved geometry (Fig. 3.1; Map 1, inside back pocket; Price, 1987).

The South Railway fault and the Railway fault merge to the west to form one fault (Railway fault) on the western limb of the Hidden Lake synform (Fig. 3.1; Stockwell, 1960; Bailes and Syme, 1989; Thomas, 1992). In outcrop, this amalgamated fault (700 m west-northwest of Hidden Lake; Fig. 3.1) forms a 5-8 m wide schistose zone (striking 350° and dipping 53° east) consisting of mainly chlorite,

with veins of quartz and pods of carbonate (Bailes and Syme, 1989). A lineation defined by rodding plunges 37° towards 136° . Shear bands developed within the planar fabric show sinistral shear, indicating that the east side (hanging-wall) moved up relative to the west side (footwall). The rocks to the east of the fault are mafic pillowed flows of the Hidden Lake formation that strike north to northeast and dip moderately to the east. The rocks to the west of this high-strain zone are not exposed.

To the northeast where the Railway fault separates into two faults (Fig. 3.1; Map 1, inside back pocket), a 1-3 m wide schistose zone strikes 041° and dips 38° southeast. A linear fabric developed within the zone plunges 35° towards 148° . Numerous Z-folds deform the planar fabric and generally show north-striking axial planes that dip moderately to the east, and have measured fold axes plunging $25-35^\circ$ towards $140-150^\circ$. The axial surfaces are parallel to the S_2 and the folds have thus been interpreted as F_2 structures. C-S fabric relationships observed within the high-strain zone indicate that the hanging-wall moved northwards over the footwall. To the south of the South Railway fault, pillowed basalts of the Hidden Lake formation strike northeast and dip moderately to the southeast (Bailes and Syme, 1989). Rocks to the north of the Railway fault consist of pillowed flows with some interbedded tuff beds, all dipping moderately to the southeast (Stockwell, 1960; Bailes and Syme, 1989).

At a location 400 m east of the branch point of the Railway and South Railway faults (Map 1, inside back pocket), the South Railway fault is marked by up to five

separate centimetre- to metre-scale ductile shear zones which consist of extensive chlorite, with quartz and carbonate veining. All five shear zones have the same general orientation (striking 047° and dipping 35° southeast) and a lineation defined by a rodding of the planar fabric (plunging 37° towards 127°). A north- to northeast-striking, shallowly to moderately dipping foliation, interpreted as S_2 , cross-cuts these five separate shear zones. Therefore, the fabric defining the five shear zones is pre- S_2 and inferred to be an S_1 foliation. Centimetre-scale Z-folds showing the same northerly strike and moderate eastward dip as the ones observed to the west, deform the ductile fabric in each of these zones. These folds are again interpreted as F_2 structures because the S_2 is parallel to their axial surfaces. These multiple shear zones contain centimetre- to metre-scale aphyric felsic dykes, which are commonly boudinaged, strongly foliated and are folded by the dominant set of F_2 Z-folds. These dykes are here concluded to have intruded during development of the South Railway fault because they contain the same strong foliation, are boudinaged within the shear zone and are deformed by F_2 folds.

To the east, the five separate shear zones join and are overturned, striking 339° and dipping 70° to the northeast (Fig. 3.1). The entire area extending south to the outlier of Missi Group rocks (Missi Wedge) and west to the Railway fault shows a diffuse zone of deformation with a fabric developed that is parallel to the mean orientation of the S_3 cleavage (striking 337° and dipping 73° northeast). The north- to northeast-striking cleavage (S_2) is overprinted by this northwest-striking fabric (S_3). As mentioned above in the section on the Hidden Lake synform (3.3.4), F_3 folds are

developed at the unconformity below the Missi Wedge. In contrast to previous interpretations (Stockwell, 1960; Bailes and Syme, 1989), it is here concluded that the region northwest of the Missi Wedge consists of a broad zone of D_3 deformation, with F_3 folds and the S_3 cleavage overprinting the South Railway fault and the Railway fault (Fig. 3.1). Two topographic lineaments observed on airphotos extend from this zone of D_3 deformation and continue to the northwest, across the Railway fault (Fig. 3.1). Presumably, these D_3 structures die out north of the Railway fault.

Further to the southeast, along the southwestern side of the Missi Wedge, the contact between the Hidden Lake basalts and the Missi Group sandstone is observed in a number of localities. A ductile fabric parallel to the basement-cover contact extends up to 1 metre into the sandstones and flattens pebbles and grains of quartz and feldspar. The volcanics exposed in a steeply east-dipping cliff face are chloritized and veined with quartz and carbonate. A schistose fabric is developed within these volcanic rocks, similar to that observed to the northwest within the South Railway fault zone. Both basement and cover rocks exhibit a ductile fabric that strikes 339° and dips 73° , and a linear fabric (elongated quartz and feldspar grains) plunging 36° towards 137° . Although the S_2 foliation was not observed anywhere along this portion of the basement-cover contact, it maintains a northward strike in both the basalts to the southwest and the sandstones of the Missi Wedge to the northeast, away from the contact. Therefore, it could be inferred that the contact-parallel fabric is an S_1 foliation, although the orientation of this fabric is parallel to the S_3 foliation that is strongly developed north of the Missi Wedge.

The Railway fault is not well exposed and, apart from the western section already discussed above, it is only observed in one other locality, 250 m north-northeast of the northeastern corner of the Missi Wedge (Fig. 3.1; Map 1, inside back pocket). It shows the same 3-5 m wide schistose zone that is dominated by extensive chlorite and veins of quartz and carbonate. Flattened basaltic pillows are aligned with the S_1 fabric which strikes 321° and dips 66° northeast.

The Catherine fault (Fig. 3.1; Map 1, inside back pocket) was not observed during mapping but was identified by Price (1987) who linked the fault with the Railway structures to the south.

The Flin Flon Lake fault is located slightly south of the Club Lake structure (Map 1; inside back pocket) and has the same chlorite-rich schistose fabric as the Railway structures (Plate 3.18). This high-strain zone splays off from fabric developed along the Club Lake structure and continues to the southwest, striking 056° and dipping 31° southeast. The ductile fabric is folded by numerous Z-folds with axial surfaces that strike north and dip moderately to the east, and fold axes plunging moderately towards the southeast. The axial surfaces are parallel to the regional S_2 which implies that they are pre- to syn- F_2 structures. This suggests that the Flin Flon Lake fault is a D_1 structure.

The curved South Railway fault surface has a calculated fold axis plunging 37° towards 135° , parallel with the axes of the Hidden Lake synform and the curvilinear Club Lake structure to the north, as well as the numerous minor folds developed within the South Railway and Flin Flon Lake fault zones (Bailes and Syme, 1989).

Plate 3.18: Flin Flon Lake fault south of Club Lake structure, northern Hidden Lake synform. This zone of deformation is typical to all of the D_1 shear zones developed within the Hidden Lake synform area (eg. South Railway fault). Deformation increases from relatively undeformed basalt (top of photo) to a well-defined schistose zone with pods of quartz (Qtz; base of photo). The fault zone is striking 045° and dipping 40° southeast. Scale card is 8 cm in length and view is to the south.

Plate 3.18

The linear fabrics within these fault zones (mean 30° plunge towards 143°) are parallel with the mean orientation of the L_2 data (Fig. 3.4) and are concluded to be correlative. The curved South Railway and Railway faults have a geometry (overturned eastern limbs and concave-to-the-south shape) similar to the folded Club Lake contact, Hidden Lake synform and Pipeline syncline, and are therefore interpreted to be folded during F_2 deformation. The S_2 cleavage maintains a northerly to northeasterly trend across these shear zones, suggesting that the fabric observed within the zones is an S_1 fabric.

Two varying interpretations on the location of the axial trace of Hidden Lake synform have been suggested. Bailes and Syme (1989) interpreted the axial trace to overprint the Railway structures without any offset, while Stockwell (1960) interpreted the axial trace to be offset by the Railway structures (Fig. 2.5). It was concluded from mapping completed during this study that the axial trace of the synform is offset by the Railway structures because of syn- to post- D_2 movement along the folded D_1 faults.

The D_1 shear zones (e.g. Flin Flon Lake fault and Railway structures) are suspected to splay from the Club Lake structure. North of the Hidden Lake synform, the high-strain zone fabric within the Flin Flon Lake fault diverges from the Club Lake contact and continues to the southwest into the Hidden Lake basalts (Fig. 3.1; Map 1, inside back cover). Although a high-strain zone fabric is not developed along this portion of the Club Lake structure, these relationships are similar to the Sepple Hill structure, where a D_1 fabric splays from the sheared basement-cover contact and

continues southwestward into the volcanic rocks.

The stratigraphic relationships across the Railway fault in the area of the Missi Wedge are not in accordance with an expected D_1 thrust fault geometry (i.e. older rocks thrust over younger rocks). The preservation of younger rocks (Missi Wedge) juxtaposed against older rocks (Hidden Lake basalts) on the eastern edge of the Missi Wedge suggests that an episode of faulting occurred prior to, or after, D_1 thrusting. A broad zone of D_3 deformation was mapped northwest of the Missi Wedge and was interpreted to overprint the D_1 Railway and South Railway structures. It is concluded that these D_3 structures extend southeastward to the Ross Lake fault and overprint the D_1 faults. Along the eastern side of the Missi Wedge, a thrust sense of displacement associated with this inferred D_3 high-strain zone could account for the current stratigraphic relationships. The amount of displacement associated with either the D_1 Railway fault or the D_3 high-strain zone is unknown but cannot be significant because the basement-cover contact is observed on either side of the two (D_1 and D_3) fault structures (Fig. 3.10-A and -D).

3.3.7 - Area north of Ross Lake

The area immediately north of Ross Lake is a structurally complex region with limited bedrock exposure. Stauffer and Mukherjee (1971) proposed the F_1 Ross Lake anticline and suggested that it is a poorly defined structure truncated by both the Ross Lake and Little Cliff Lake faults (Fig. 2.5). The existence of this fold is inferred on the basis of the outcrop pattern of the basement-cover contact (Fig. 2.5). The Flin Flon folds are a series of three F_2 folds that apparently do not overprint either the Ross Lake anticline or the Ross Creek syncline (Fig. 2.5; Stauffer and Mukherjee, 1971). The axial planes of these folds dip about 60° to the east and their hinges are

calculated to plunge about 30° towards the southeast (Stauffer and Mukherjee, 1971).

The third structure of consequence is the Little Cliff Lake fault. Stauffer and Mukherjee (1971) pointed out that there is no well-defined topographic lineament that would suggest a fault, the rocks in the area do not show any signs of fault deformation and the structure would be difficult to map if not for the marked displacement between the various stratigraphic units. This marked displacement refers to the juxtaposition of volcanic rocks next to units 4, 5 and 6 of the Little Cliff Member (Fig. 2.5; Fig. 3.12-A; Stauffer and Mukherjee, 1971). Typically, the Little Cliff Member is separated from the Flin Flon arc assemblage by the Beaverdam Member, an extensive unit that is up to 1600 m thick (Stauffer, 1990). This stratigraphic relationship is maintained throughout most of the field area (except near the Club Lake structure). Stauffer and Mukherjee (1971) initially postulated that the Little Cliff Lake fault could be a conjugate structure to the Ross Lake fault. They inferred that a conjugate structure would require a north-dipping fault surface, with the north side having moved up relative to the south side (Stauffer and Mukherjee, 1971). The stratigraphic relationships along this portion of the basement-cover contact show an opposite thrust relationship (Fig. 3.12-A; volcanic rocks adjacent to the Pipeline syncline) suggesting that the rocks southwest of the fault moved northward, over the rocks northeast of the fault (Stauffer and Mukherjee, 1971). These two authors concluded that the Little Cliff Lake fault is a reverse oblique-slip fault, the south side having moved up and to the northwest with respect to the north side.

The major limitation on interpreting this area is the absence of outcrop.

Figure 3.12. Two hypotheses to explain the limited outcrop pattern north of Ross Lake. (A) illustrates the thrust model, showing the volcanic rocks thrust northward above sedimentary rocks, along the Little Cliff Lake fault. (B) shows an interpretation of an inlier of volcanic rock adjacent to a second, syn-Ross Lake fault that extends southward through Ross Lake.

Figures 3.12-A and -B show two structural interpretations consistent with the distribution of outcrops north of Ross Lake. At the two eastern-most exposures of the basement-cover contact, the contact dips steeply to the east-northeast (Fig. 3.12-A). At the locality where the basement-cover contact dips 60° northeast (Fig. 3.12-A), the contact is a well-preserved, overturned unconformity with no evidence of shearing in the regolith or in the pebbly sandstone. The contact further to the east (dipping 62° northeast) is faulted, with no regolith preserved in the volcanic rock or conglomerate in the Missi Group. The only other exposure of the basement-cover contact is located further to the west where it is vertical (Fig. 3.12-A).

Two models (Fig. 3.12-A and -B) were considered during the interpretation of this area. The first (Fig. 3.12-A) shows the thrust-fault model (Stauffer and Mukherjee, 1971) and the second shows an alternative interpretation of a folded basement inlier. The second model depicts an overturned F_1 anticline cored by a volcanic basement high. The inlier model must be discarded because an excessive thickness (1300-1400 m) of Missi Group rocks (units 2 and 3, Stauffer, 1990) is missing between the inlier and the Pipeline syncline area to the northwest. This model would also require significant relief on the volcanic basement paleoerosional surface.

In the model shown in Figure 3.12-A, the Little Cliff Lake fault accounts for the juxtaposition of Flin Flon arc assemblage adjacent to units 3, 4, and 5 of the Missi Group (Stockwell, 1960, Stauffer and Mukherjee, 1971). Because the Beaverdam Member is missing, a fault must exist between the basement and cover rocks (Stauffer

and Mukherjee, 1971). Stauffer and Mukherjee (1971) initially postulated that this fault could be a conjugate structure to the Ross Lake fault. To be consistent with mapping during this study, this fault must have a folded trace. It therefore cannot be conjugate to the D_4 Ross Lake fault because all folding in the study area occurred prior to D_4 faulting. A thrust fault is required to account for the observed relationships of volcanic rocks adjacent to strata of the upper Missi Group (Little Cliff Member). Stauffer and Mukherjee (1971) concluded their interpretation by saying that "the Little Cliff Lake fault could have an outcrop pattern similar to the Club Lake fault", but did not assign a specific age (e.g. D_1) to the structure. It is here concluded that the Little Cliff Lake fault is a D_1 thrust fault because of the apparent juxtaposition of Flin Flon arc assemblage adjacent to the Pipeline interference basin (cf. D_1 Club Lake structure juxtaposing Hidden Lake basalts over the Flin Flon Creek syncline). Correlation of Little Cliff Lake fault with the Club Lake structure is discussed in section 3.4.

The detailed overprinting relationships between F_1 - F_2 folding and the D_1 Little Cliff Lake fault cannot be accurately understood because of the poor outcrop exposure. Therefore, the following discussion is only a suggested interpretation for this area. The designation of this fault as a D_1 structure requires that the axial trace of the F_2 Pipeline syncline must cross the Little Cliff Lake fault (south of Little Cliff Lake; Fig. 3.1) and be truncated against the Ross Lake fault. Presumably, the Little Cliff Lake fault is folded by this F_2 syncline but the effects are masked by Little Cliff Lake and the D_4 Ross Lake fault. To the southeast, where the Little Cliff Lake fault

lies east of the highway (Fig. 3.12-A), it adopts an east-west strike. This change from a southeast trend to an east-west trend defines an antiformal structure which could possibly be explained by D_2 deformation.

Stauffer and Mukherjee (1971) concluded that the F_2 Flin Flon folds do not deform the F_1 Ross Lake anticline or the Little Cliff Lake fault. Given the outcrop pattern of the volcanic and sedimentary rocks observed along this east-west striking portion of the fault, the Little Cliff Lake fault cannot have a geometry parallel with the folded basement-cover contact located 50-200 m to the south (Fig. 3.12-A). Intersections between the limited number of basement-cover contacts suggest that the fold axes for the folded basement-cover contact should plunge steeply to the east, but this would be inconsistent with the geometry typical of F_2 folds (moderately plunging to the southeast). Also, bedding-cleavage (S_2) relationships along the folded basement-cover contact do not support an expected F_2 fold geometry. Therefore, it is suggested that the basement-cover contact is deformed by F_1 folds. It is also inferred that these F_1 folds formed prior to D_1 thrusting because the proposed trace of the Little Cliff Lake fault is only weakly folded compared to the strongly folded basement-cover contact. Other evidence of F_1 folding occurring prior to D_1 faulting is observed at Sepple Hill and along the Club Lake structure.

Stauffer and Mukherjee (1971) proposed the F_1 Ross Lake anticline to account for the F_1 folds developed along the basement-cover contact (Fig. 2.5). The inferred axial traces of these F_1 folds do not correlate with the geometry of the Ross Lake anticline. Therefore, an alternative F_1 fold geometry has been proposed (Fig. 3.12)

based on interpretations made during this study.

In summary, a possible interpretation based on the limited field data of this area is that the basement-cover contact was folded by three F_1 folds and then thrust northwards along the D_1 Little Cliff Lake fault. The open folds of the Little Cliff Lake fault are most likely due to F_2 folding. The F_2 Pipeline syncline must also deform the Little Cliff Lake fault but the effects are not preserved due to subsequent faulting (i.e. Ross Lake fault). The area immediately south of Ross Lake was not mapped during this study and so the extent of the Flin Flon folds is unknown.

3.3.8 - Microscopic relationships within the Flin Flon arc assemblage

In the volcanic rocks from the northern study area (South Railway-Club Lake structure area) a single dominant fabric is observed in rocks from the bedding-parallel shear zones (i.e. South Railway fault) and along the Club Lake structure (thin sections were cut transverse to the foliation). Within the volcanic rocks (South Railway fault), the pervasive fabric consists entirely of aligned chlorite and epidote, with veins of quartz and carbonate. The Club Lake structure (basement-cover contact) shows a moderate to strong fabric defined by aligned hornblende, biotite, chlorite and epidote, with veins of quartz and carbonate. Where observed, the hornblende is aligned in the dominant fabric (i.e. Club Lake structure), which is predominantly defined by chlorite. Alignment of inequant quartz and feldspar grains defines the fabric in the sandstones.

In thin sections cut transverse to the pervasive northeast striking cleavage (S_2)

and parallel with the L_2 , a strong fabric is developed and defined by peak metamorphic minerals (Ambrose, 1936b; Bailes and Syme, 1989; Fedorowich et al., 1995). Depending on the grade of metamorphism, the S_2 fabric is defined by alignment of hornblende (between Railway faults and the Club Lake structure), needles of actinolite (South Railway fault area), biotite and extensive chlorite (Fig. 2.3; Digel and Gordon, 1995). The peak-metamorphic minerals (hornblende and biotite) were also aligned in the fabric from the D_1 shear zones (i.e. Club Lake structure). This relationship suggests that this D_1 fabric is actually a composite S_1 - S_2 foliation, or that the angular relationships between D_2 mineral growth and the S_1 fabric were not observable in the plane of the thin section.

Due to the spaced, domainal nature of the S_3 cleavage, it is rarely observed in thin section. The S_3 foliation forms 0.2-0.6 mm wide zones consisting of quartz and chlorite that realign the hornblende crystals (Plate 3.19). The hornblende crystals realigned in the S_3 foliation do not show any indication of alteration due to the overprinting S_3 event. The S_3 high-strain zones that dissect the Hidden Lake basalt area were examined in a thin section cut transverse to the fabric of one of these zones. The strong fabric is defined by chlorite, biotite, epidote, quartz and carbonate with no earlier fabric preserved.

In thin sections cut transverse to the L_2 fabric, the peak metamorphic minerals (specifically hornblende) form relatively equant to lensoidal shapes, with the long axes of these shapes aligned in a moderately developed S_2 foliation (Plate 3.20).

Thin section study of structural fabrics reveals three important relationships:1)

Plate 3.19: Photomicrograph (plane-polarized light) from the Hidden Lake synform area, north of the Railway fault (thin section is cut transverse to the S_2 and parallel to the L_2). Hornblende (Hbl), biotite (Bt) and minor chlorite (Chl) define the pervasive S_2 fabric. The S_3 cuts diagonally through the section and is defined by chlorite and quartz (Qtz). A hornblende crystal is re-aligned in the S_3 fabric (centre of photo). Width of photo is 2 mm.

Plate 3.20: Photomicrograph (cross-polarized light) from the Hidden Lake synform area, north of the Railway fault (this thin section is from the same rock as Plate 3.19 and is cut transverse with the L_2). The long axis of the equant- to lensoidal-shaped hornblende crystals (note: different birefringence due to cross-polarized light) are aligned in a weakly-developed S_2 foliation. The change in intensity of the S_2 fabric from Plate 3.19 (strong) to Plate 3.20 (weak) reflects the elongation component of the D_2 fabric and demonstrates that these rocks are L-S tectonites. The view in this section is looking 'down' the lineation and so the true character of the D_2 fabric is observed. Width of photo is 1 mm.

Plate 3.19

Plate 3.20

Rocks from the D_1 high-strain zones (i.e. Club Lake structure and Railway faults) show a moderate to strong fabric defined predominantly by extensive chlorite and epidote, with minor hornblende and biotite (peak metamorphic minerals). This suggests that the fabric within these D_1 zones is actually a composite S_1 - S_2 foliation;

2) Peak metamorphism is associated with the D_2 event, based on the following deformation-metamorphic relationships: (a) peak metamorphic minerals (chlorite, actinolite and hornblende) are aligned in the S_2 fabric; (b) the long axes of lensoid metamorphic minerals (viewed transverse to the lineation) are moderately aligned in the S_2 foliation; and (c) the S_3 fabric realigned peak metamorphic minerals and is associated with retrograde mineral growth (i.e. chlorite); and 3) Inequidimensional minerals were aligned parallel to S_2 and L_2 , suggesting that these rocks are L-S tectonites.

The locations of all metamorphic minerals observed during this study are generally consistent with the established isograds (Fig. 2.3; Digel and Gordon, 1995), with the exception of specific retrograde zones (S_3 high-strain zones, Railway structures, and Club Lake structure). The metamorphic isograds depicted on Figure 2.3 (Digel and Gordon, 1995) do not appear to be folded by the Hidden Lake synform, suggesting that peak metamorphism occurred after the Hidden Lake synform developed. These relationships will be discussed in the following chapter.

3.4 - Brittle-ductile fault structures

The Cliff Lake, Channing and Ross Lake faults have been previously interpreted as sinistral oblique-slip, brittle-ductile reverse faults (Ambrose, 1936b; Stauffer and Mukherjee, 1971; Bailes and Syme, 1989; and Fedorowich, 1995). These faults are poorly exposed in the field area, but they form topographic lineaments, occurring at the base of cliffs or along the centre of valleys. The Cliff Lake fault (Fig. 3.1) is the oldest of the three faults, has been associated with D₃ deformation (this study) and is folded by the Embury Lake antiform north of the field area (Stauffer and Mukherjee, 1971). The Ross Lake and Channing faults are designated as D₄ structures (this study, Table 1) because they offset the Cliff Lake fault and the Embury Lake antiform north of the field area (Stauffer and Mukherjee, 1971). Fedorowich et al. (1995) used K-feldspar to calculate an ⁴⁰Ar/³⁹Ar plateau age of 1691 ^{+6/-6} Ma for the main stage of Ross Lake fault activity. All three faults (Ross Lake, Channing, and Cliff Lake) strike north-northwest and dip steeply to the east (Stauffer and Mukherjee, 1971). Stauffer and Mukherjee (1971) described the three faults as brecciated, mylonitized, crenulated, veined and altered by retrograde quartz-albite-chlorite grade metamorphism.

Stauffer and Mukherjee (1971) estimated the net slip of the Ross Lake fault by using the displaced basement-cover contact in the southern study area (north and south limbs of the Ross Creek syncline) and the displaced Channing fault slightly north of the field area. They assumed that the fault surface strikes 343° and dips 65° east, and

determined that the net slip plunges 42° towards 138° . They calculated that the fault displacement is 762 m in the south of this study area and increases to 1372-1525 m, 400 m north of this study area, with the east side moving up and to the northwest (sinistral-oblique; Stauffer and Mukherjee, 1971).

Stauffer and Mukherjee (1971) made several important interpretations along this fault structure. To test these interpretations and to examine displaced structures recognized during this study, a fault plane map of the Ross Lake fault was constructed (Fig. 3.13). The primary assumption underlying this reconstruction is the amount of movement along the Ross Lake fault. Stauffer and Mukherjee's (1971) estimate that the movement in the southern field area is 762 m (based on displaced basement-cover contacts) was tested and found to be reasonable. The Channing fault was not mapped during this study and so Stauffer and Mukherjee's (1971) estimate of 1372-1525 m of displacement in the area to the north was used. Therefore, for the area where this fault plane map was constructed, 1000 m was assumed to be the net displacement. The fault is assumed to strike 343° and dip 65° east, with a net slip plunging 42° towards 138° (Stauffer and Mukherjee, 1971). The variation in the net slip from the southern area to the northern area suggests that there is a component of rotation along this fault surface. It also implies that the orientation of the net slip vector could change (from south to north) with respect to the inferred rotation. Therefore, a second assumption used during the construction of the fault plane map was that the net slip (1000 m) remains the same and that the net slip vector does not change along this fault plane map.

Figure 3.13. Fault plane map of the northern portion of the Ross Lake fault. Orientation of fault is assumed to strike 343° and dip 65° northeast. The net slip is assumed to be 1000 m with a rake of 48° southeast. Ps: Pipeline syncline; FFCs: Flin Flon Creek syncline; CLs: Club Lake structure; LCLf: Little Cliff Lake fault; b-c contact: basement-cover contact. The orientation and geometry of all structural features at the horizontal datum are based on data from surface mapping. Dashed lines represent hanging-wall features; solid lines represent footwall features.

In the northernmost portion of the study area, Stauffer and Mukherjee (1971) concluded that the Flin Flon Creek syncline on the west side of the Ross Lake fault is continuous with the F_1 fold within the Pipeline interference basin, despite the apparent contradiction (dextral as opposed to sinistral) in displacement (Fig. 2.5). Stauffer and Mukherjee (1971) explained this apparent dextral offset of the F_1 axial trace by comparing the dip of the axial surface and the movement vector associated with the Ross Lake fault. The dip of the axial surface is shallower than the movement vector for the fault; therefore it has an apparent dextral offset along this sinistral-oblique fault (Stauffer and Mukherjee, 1971).

This interpretation was tested during this study by constructing a fault-plane map of the Ross Lake fault. The fold hinge generated from measurements of the folded conglomerate unit in the core of the Flin Flon Creek syncline was used as a piercing point to test the location of the corresponding fold hinge in the hanging-wall (Fig. 3.13). Locality 3 (Fig. 3.1) indicates where the fold hinge of the Flin Flon Creek syncline (at the base of the conglomerate unit) should intersect the surface in the hanging-wall, assuming 1000 m of displacement. This calculation, together with the fault plane map (Fig. 3.13), shows that the Flin Flon Creek syncline cannot be correlated with an F_1 fold hinge in the core of the Pipeline syncline because the corresponding fold axis in the hanging-wall does not lie within any of the mapped F_1 axial planes (Fig. 3.1). Therefore, it can be concluded that none of the F_1 folds in the core of the Pipeline syncline is the hanging-wall continuation of the F_1 Flin Flon Creek syncline.

The fault plane map (Fig. 3.13) was also used to test the relationship between the Club Lake structure and the Little Cliff Lake fault. Correlation began on the footwall (western) side of the Ross Lake fault because of the known orientation of the Club Lake structure. The curved trace of the Club Lake structure was drawn by assuming that its northeast-dipping attitude at surface is folded into a southwest-dipping attitude at depth. This relation is shown in cross-section (Fig. 3.10-C) and is supported by the surface trace of the Club Lake structure, further to the west (Fig. 3.9-A). The curved trace of Club Lake structure was displaced to a location in the hanging-wall (Fig. 3.13). By extrapolating this hanging-wall trace back to the horizontal datum, the Club Lake structure correlates, within error, to the hanging-wall trace of the Little Cliff Lake fault. The Little Cliff Lake fault is not exposed at surface and so its exact attitude is unknown.

Similarities are shown with respect to the stratigraphic relationships preserved within the footwall Missi Group sedimentary rocks structurally below both the Little Cliff Lake fault and the Club Lake structure. Comparisons can be made by examining the expression of these features in the hanging-wall of the Ross Lake fault (Fig. 3.13). The Missi Group beneath the Little Cliff Lake fault faces to the north, away from the assumed south-dipping fault surface (Fig. 3.13), but is folded by the Pipeline syncline into a south-facing orientation further to the north. The Missi Group beneath the Club Lake structure also faces to the north and is deformed by the Flin Flon Creek syncline (Fig. 3.13). The conglomerate from the Pipeline syncline is suggested to be folded by an anticline above the horizontal datum because it must adhere to the north facing

relationships beneath the Club Lake structure. Evidence for this proposed anticline which is defined by the conglomerate was not observed during surface mapping. This fold could possibly be an F_1 structure that is not developed at the structural level of the Club Lake structure/Flin Flon Creek syncline.

Stratigraphic facing directions from within the volcanic rocks of the hanging-wall also show broadly similar relationships. In the immediate hanging-wall of the Club Lake structure (at surface), regolith indicates that the basement-cover contact faces to the north, whereas to the south in the Hidden Lake synform, two outliers of Missi rocks indicate an upright to south-facing basement-cover contact. The basement-cover contact was not observed in the hanging-wall above the Little Cliff Lake fault. Further to the south, the basement-cover contact is mapped as facing to the south (Fig. 3.13). The dip (steeply south-dipping) of the basement-cover contact in the footwall of the Ross Lake fault (western shore of Ross Lake; Fig. 3.1) is in marked contrast with the assumed dip of the basement-cover contact in the core of the Hidden Lake synform (weakly south-dipping below the Missi outliers). The significant steepening of this surface towards the south could be due to folding related to the F_1 Ross Creek syncline.

In summary, it is concluded that the Club Lake structure continues east of the Ross Lake fault as the Little Cliff Lake fault. This conclusion is primarily based on the interpretation of the Little Cliff Lake fault as a D_1 thrust which juxtaposes volcanic rocks against the Little Cliff Member of the Missi Group. Also, the fault plane map of the Ross Lake fault shows that the hanging-wall trace of the Club Lake

structure could be correlative to the trace of the Little Cliff Lake fault, and that the stratigraphic relationships in the footwall and in the hanging-wall to both structures are the same. The correlation shown between the displaced hanging-wall and footwall basement-cover contacts on the southern section of the fault plane map indicates that the displacement (1000 m) and the net slip vector (pitching 48° south) are reasonable assumptions.

3.5 - Summary of structural geology

The three generations of folds (F_1 , F_2 , F_3) and associated foliations (S_1 , S_2 , S_3) that were documented during this study match the established structural model for the Missi Group sedimentary rocks (Table 2, chapter 4; Stauffer and Mukherjee, 1971) and can be correlated to the deformation recorded within the Flin Flon arc assemblage. The deformation events that occurred in the study area are summarized in Table 1 and described in detail below.

The Burley Lake syncline is preserved within volcanic rocks in the southwest portion of the field area and is the only observed structure that predates Missi Group deposition. There is no associated cleavage in the area.

The S_1 foliation is not extensively developed throughout the study area and tends to be preserved in isolated lenses of fine-grained shale (Missi Outlier) and within the footwall volcanic rocks of the Callinan deposit (Thomas, 1992, 1994). Where present, it is an east-west striking penetrative cleavage. A number of F_1 folds have

been identified on the basis of younging reversals, map patterns, and overprinting by the regional S_2 foliation (Stauffer and Mukherjee, 1971); only one macroscopic F_1 fold has developed an S_1 axial planar cleavage (southern Missi Outlier). Examples of these folds include (from north to south) the Flin Flon Creek syncline, the Ross Lake anticline, the Ross Creek syncline and the Missi Outlier (Fig. 3.1; Stauffer and Mukherjee, 1971). These F_1 structures were originally closed to tight, east-west striking folds with axial surfaces upright and both south- and north-dipping (Stauffer and Mukherjee, 1971). These F_1 axial surfaces are upright to steeply north-dipping in the southern field area and change to moderately to steeply south-dipping in the northern field area. The extensive variation in strike of the F_1 axial surfaces (Fig. 3.1) is a result of overprinting by F_2 folds, producing type-I to type-II interference patterns (Ramsay, 1967).

A number of D_1 high-strain zones (Club Lake structure, Railway faults, Sepple Hill shear zone) preserve a ductile fabric that is overprinted by subsequent deformation (i.e. S_2 cleavage and F_2 folds; Bailes and Syme, 1989). In detail, the fabric within these D_1 zones is defined by chlorite, with minor hornblende and biotite. This fabric must be a composite fabric (S_{1+2}) because of the alignment of the peak metamorphic minerals. F_1 folding predates development of these D_1 shear zones because the D_1 Sepple Hill shear zone and Club Lake structure are developed on the overturned limbs of F_1 folds.

The Hidden Lake synform is also overprinted by the S_2 cleavage but its characteristics (west-verging, overturned fold with southeast plunging fold axis; Bailes

and Syme, 1989) match the geometry of the F_2 folds documented within the Missi Group. The Hidden Lake synform folds the D_1 high-strain zones (Club Lake structure and Railway faults; Bailes and Syme, 1989) and therefore is described as an F_2 fold. These relationships will be discussed in detail in the following chapter.

The S_2 foliation is a penetrative cleavage that strikes north to northeast and dips shallowly to moderately to the east in the northern study area (Stauffer and Mukherjee, 1971; Fig. 3.4). In the southern region of the study area, this foliation adopts a northerly strike with a steeper, eastward dip. Throughout the area, S_2 represents the principal elongation and flattening fabric (i.e. $L > S$) within the rocks of the Missi cover sequence (Stauffer and Mukherjee, 1971) and developed at peak metamorphic conditions (Ambrose, 1936b; Bailes and Syme, 1989; Fedorowich et al., 1995). In the northern portion of the study area, the F_2 structures (Pipeline syncline and Hidden Lake synform; Fig. 2.5) are tight, west-verging, overturned folds (Stauffer and Mukherjee, 1971; Bailes and Syme, 1989). In the south, F_2 folds are closed and only locally overturned (Stauffer and Mukherjee, 1971). Due to the variations in the geometry of the F_1 structures, the F_1 - F_2 fold-interference patterns in the southern and northern parts of the study area are somewhat different.

The S_3 foliation was recognized in this study as a spaced, domainal cleavage that strikes northwest, dips steeply to moderately northeast, is heterogeneously developed throughout the area and is axial planar to rare F_3 folds (Fig. 3.5). D_3 deformation also formed high-strain zones which are 0.5-5 m in width and extensively dissect the volcanic and sedimentary stratigraphy in the Hidden Lake synform-Pipeline

syncline area. In S_3 high-strain zones, clasts within the conglomerate beds and pillows in the volcanic rocks are realigned and flattened in the S_3 cleavage plane. The S_2 cleavage is overprinted by S_3 within these high-strain zones.

A regional lineation was mapped throughout the northern half of the study area in both the Missi Group and Flin Flon arc assemblage (Stauffer and Mukherjee, 1971; Bailes and Syme, 1989). It is defined by the elongation of volcanic pillows, clasts within the conglomerate and volcanoclastic beds, and quartz and feldspar grains in the matrix of the sandstones and granites (Stauffer and Mukherjee, 1971; Bailes and Syme, 1989). In areas where the lineation is well developed, clasts in conglomerate may show aspect ratios of up to 7:1 (c.f. Stauffer and Mukherjee, 1971). This lineation formed during D_2 deformation (i.e., L_2), consistent with the interpretations of Stauffer and Mukherjee (1971) and Fedorowich et al. (1995), who associate the lineation with S_2 and growth of peak-metamorphic assemblages. However, the extension lineation is also subparallel to most F_1 , F_2 and F_3 fold axes and the intersection of S_2 and S_3 . In S_3 high-strain zones, re-aligned features (e.g. pebbles) are parallel with the L_2 , and so it is unknown if there was any elongation in the D_3 event.

Observations made during this study of the S_2 and L_2 fabrics suggest that the type of strain during the D_2 event varies from south to north across the field area. The D_2 fabric in rocks from the southern field area (Mud Lake syncline area) is defined mainly by an S_2 , with a very weakly developed L_2 . Therefore, these rocks were deformed by oblate strain during the D_2 event, producing $S > L$ tectonites. In

the northern field area (Pipeline syncline-Hidden Lake synform), the D_2 fabric is defined by both an S_2 and an L_2 , but the L_2 is the dominant fabric element. Therefore, the rocks in the northern study area were deformed by prolate strain, producing $L > S$ tectonites. The S_1 fabric was only rarely developed within the field area so the state of strain associated with this event cannot be characterized. The S_3 fabric produces a re-alignment of features (e.g. pebbles) into the upright foliation plane. A linear fabric element associated with this event is not observed in the southern field area, and, if present in the northern field area, cannot be distinguished from the dominant L_2 fabric. Therefore, it is concluded that rocks deformed by oblate strain during the D_3 event.

◆ Chapter 4 - Discussion ◆

The principal advance in this study has been the correlation of deformation structures between the sedimentary cover (Missi Group) and volcanic basement (Flin Flon arc assemblage). The three generations of folds and foliations observed in the Missi Group sedimentary rocks in this study match, in general, the sequence established by Stauffer and Mukherjee (1971; Table 2, see below). The following discussion examines several key issues pertinent to the three-dimensional geometry and deformation history of the Flin Flon area. These include: (1) pre-Missi Group deformation; (2) D_1 deformation; (3) D_2 deformation; (4) D_3 and D_4 deformation; (5) relationship to the regional tectonic setting; and (6) relationships between surface and mine geology. Also included is a list of the main advances on previous work made in this study, followed by the final conclusions and recommendations for further studies.

4.1 - Deformational summary

4.1.1 - Pre-Missi Group deformation

The Burley Lake syncline is interpreted to be the only structure that provides evidence for deformation prior to Missi Group sedimentation (Stockwell, 1960; Bailes and Syme, 1989). At a number of localities in the study area, the volcanic rocks form angular unconformities below the overlying Missi Group rocks. This also suggests deformation occurred prior to Missi Group sedimentation.

4.1.2 - D₁ deformation

There are a number of map-scale folds and faults in the study area that are interpreted to have formed during the D₁ event. The folds consist of (from south to north) the Missi Outlier, the Ross Creek syncline, the Ross Lake anticline and the Flin Flon Creek syncline. The faults consist of the Sepple Hill shear zone, the Little Cliff Lake, Railway, Catherine, and Flin Flon Lake faults, and the Club Lake structure. The ages of all these features as pre-D₂ are inferred on the basis of a cross-cutting pervasive cleavage (S₂) and/or F₂ folding. Based on the relationships between the D₁ faults and the F₁ folds, it can be concluded that F₁ folding occurred prior to and during D₁ thrusting. The basement-cover contact varies in character throughout the study area and it is deformed by numerous D₁ structures. A quantitative estimate of the minimum amount of displacement has been made for the Club Lake structure, based on a north-south oriented cross-section and constraints offered by Hudson Bay Exploration and Development (HBED) drillholes. Finally, the timing of D₁ deformation can be bracketed by emplacement of the Boundary Intrusions and the onset of peak metamorphism (D₂).

The F₁ axial planes vary in strike throughout the study area due to F₂ folding. The F₁ axial surfaces were initially upright to steeply north-dipping in the southern field area and moderately to steeply south-dipping in the northern field area. These variably dipping F₁ axial surfaces define a moderately-developed fan-fold structure.

Based on kinematic indicators for reverse thrusting (this study; Fedorowich et al., 1995), it can be concluded that the D₁ shear zones produced internal imbrication

within the volcanic stratigraphy (South Railway, Railway, Catherine and Flin Flon Lake faults) and resulted in the volcanic basement being thrust over the sedimentary cover sequence (Little Cliff Lake fault, Sepple Hill shear zone and Club Lake structure). The shear zones within the volcanic basement (i.e. Flin Flon Lake and Railway faults) are interpreted to be splays that branch from a basal thrust (Club Lake structure; cross section Z-Z', Fig. 4.1, inside back cover). The attitudes of these D_1 shear zones vary due to F_2 folding but they are interpreted to have originated as east-west striking. Almost all the linear fabrics preserved within these structures are parallel with the regional lineation (L_2 ; Stauffer and Mukherjee, 1971) and therefore do not record the original D_1 thrust direction. The only evidence for an L_1 linear fabric was observed along the Sepple Hill shear zone where striations on the S_1 plunge moderately towards the south-southeast.

Evidence for F_1 folding predating D_1 development of shear zones is preserved at Sepple Hill, the area north of Ross Lake, and along the Club Lake structure. The sheared basement-cover contact (S_1 fabric) in the Sepple Hill area is overturned and dips to the south. The D_1 Sepple Hill shear zone is interpreted to have formed after F_1 folding because the shear zone is developed on an overturned section of the basement-cover contact. The basement-cover contact north of Ross Lake was interpreted to be folded by the three F_1 folds. It was proposed that these folds of the basement-cover contact do not deform the suggested trace of the Little Cliff Lake fault (Stauffer and Mukherjee, 1971; this study). Therefore, it was inferred that these F_1 folds were thrust northward along this D_1 structure. In the north of the study area

along the Club Lake structure, it was concluded that F_1 folding occurred prior to D_1 thrusting because the D_1 shear zone is developed on the overturned limb of an F_1 fold (i.e. Ross Lake anticline, south of Club Lake structure). However, in the same area (Fig. 3.8-B), the S_1 fabric preserved along almost the entire length of the Club Lake structure is locally folded by a set of north-verging F_1 folds that have axial surfaces parallelling the mean attitude of the D_1 Club Lake fabric (striking 055° and dipping 45°). It is inferred that these F_1 folds formed during thrusting and the axial surfaces were rotated into alignment with the dominant S_1 fabric during progressive D_1 deformation. Therefore, development of the map-scale F_1 folds (e.g. Flin Flon Creek syncline) predated D_1 thrust development, D_1 thrusts developed on the overturned limbs of these F_1 folds and rare mesoscopic F_1 folds continued to form during D_1 thrusting.

The character of the basement-cover contact varies throughout the study area. In the southern region, an unsheared, upright unconformity defines the basement-cover contact. In the northern region, it is defined by either a preserved unconformity, a thrust fault, or a thrust fault developed along an overturned unconformity. At Sepple Hill, the basement-cover contact is a sheared, overturned (south-dipping) unconformity, along which the Flin Flon arc assemblage was thrust northward over Missi Group sedimentary rocks. Based on limited field evidence, the Little Cliff Lake fault is presumed to define the basement-cover contact south of the Pipeline interference basin and is also inferred to thrust volcanic basement rocks northward over sedimentary cover sequence. The western (Saskatchewan) section of

the Club Lake structure is defined by a thrust fault which displaced basement rocks northwards over the cover sequence (Bruce, 1918; Ambrose, 1936a; Stockwell, 1960; Stauffer and Mukherjee, 1971; Bailes and Syme, 1989). The Club Lake structure is also a thrust fault along the eastern (Manitoba) section, but is there developed along an overturned unconformity. The evidence for this interpretation is the existence of regolith within the hanging-wall rocks above the south-dipping Club Lake structure. Farther to the east, an unsheared unconformity with no evidence for displacement defines the basement-cover contact. In order to explain the existence of both a well-preserved unconformity and a significant basement-on-cover overlap (see below), it is concluded that the Club Lake structure must have stepped structurally down into the Missi Group, and therefore must be juxtaposing Missi on Missi in areas where the unconformity is preserved. As there is no outcrop north of the undeformed unconformity, this interpretation could not be tested.

The stratigraphic younging directions indicated by the regolith below the Missi outliers on the eastern limb of the Hidden Lake synform (upright) and at the basement-cover contact to the north, along the Club Lake structure (overturned; Fig. 3.9-D) suggest the existence of a basement-cored F_1 anticline (here named the Ross Lake anticline) south of the Club Lake structure. This is consistent with the asymmetry of the north or northeast-verging F_1 Flin Flon Creek syncline (Ambrose, 1936a).

A series of drill holes in the Hidden Lake synform area intersected the

basement-cover contact at depth, suggesting that the contact has a consistent moderate southward dip (45° - 50° ; Fig 3.10-A, 3.11; T. Baumgartner, D. Price, and J. Pickell, pers. comm., 1995). Stauffer and Mukherjee (1971) estimated 1067-1830 m of northwestward thrust displacement on the Club Lake structure. Figure 3.10-B shows a northwest-striking cross-section that was positioned to take advantage of the three HBED drill holes and to test Stauffer and Mukherjee's (1971) estimate for the fault displacement. A minimum displacement of 2600 m is defined assuming that the Club Lake structure was displaced in a northwestward direction.

There are almost no slip lineations preserved on any of the D_1 thrust surfaces. Therefore, the fold vergence of the F_1 folds in the northern study area must be used to approximate the thrust direction. The only L_1 fabric was observed at Sepple Hill, where a weakly developed, south to southeast-plunging lineation is preserved. It is concluded that the D_1 faults all had a northerly-directed thrust sense, consistent with the L_1 fabric (Sepple Hill) and the asymmetric F_1 folds (north- to northeast-verging: Flin Flon Creek syncline). A minimum basement-on-cover overlap of 2900 m was calculated assuming north-verging thrusting in Figure 3.10-C, whereas displacement calculated on Figure 3.10-B is 2600 m. The difference in the amount of displacement between the two cross-sections (Fig. 3.10-B and -C) is dependent on their respective orientation (north verses northwest) and F_2 (Hidden Lake synform) folding, which deformed the Club Lake structure and resulted in a folded D_1 fault plane. The north-striking cross-section (Fig. 3.10-C) must accommodate for the eastern overturned limb of the folded fault plane, and therefore shows a greater displacement for D_1 basement-

on-cover-overlap. In both cases, the minimum thrust displacement constrained by drill results is significantly more than Stauffer and Mukherjee's (1971) estimate.

A maximum age limit on D_1 deformation can be constrained by the emplacement of the Boundary Intrusions (1842^{+3}_{-3} Ma, Heaman et al., 1992). During this study, both an S_1 fabric associated with high-strain zones, and the S_2 and S_3 cleavages, were recognized within these intrusions. Therefore, the timing of D_1 thrusting postdates the age of emplacement. A minimum age for the D_1 event is constrained by the onset of peak metamorphism (S_2/F_2 development: ca. 1820 Ma; Fedorowich et al., 1995) which is associated with D_2 deformation. Therefore, the D_1 event occurred between ca. 1840-1820 Ma.

4.1.3 - D_2 deformation

West-verging, closed to tight, overturned folds with an associated lineation and a pervasive axial-planar foliation were formed during the D_2 event. For the most part, sedimentary clasts, volcanic fragments and amygdules are flattened and elongated within the S_2 and L_2 fabrics. The D_2 event is associated with peak metamorphism (Ambrose, 1936b; Bailes and Syme, 1989; Digel and Gordon, 1995; this study), which constrains the age of deformation to 1820-1790 Ma (Fedorowich et al., 1995). The dominant D_2 structures formed in the Missi Group are the Mud Lake and Pipeline synclines (Stauffer and Mukherjee, 1971).

The geometry of the Hidden Lake synform is not consistent with the F_1 Flin Flon Creek syncline, implying that the folding event that caused it either postdates or

predates D_1 deformation. There does not appear to be an expression of the Hidden Lake fold in the sedimentary strata to the north of the Club Lake structure (Map 1, inside back pocket). The folded concave-to-the-south shape of the Club Lake structure requires that the Hidden Lake synform developed after F_1 , and it is therefore designated as an F_2 structure. The calculated fold hinge for the Hidden Lake synform is also coaxial to the fold hinge of the F_2 Pipeline syncline (Bailes and Syme, 1989). However, as illustrated in Figure 3.4, S_2 cuts across the hinge of the Hidden Lake synform. The Hidden Lake synform is thus interpreted to be an early D_2 structure that was subsequently transected by the S_2 regional cleavage. The F_2 folds developed along the Club Lake structure show a slightly different relationship and have the S_2 foliation as an axial planar cleavage. This suggests that locally, the S_2 cleavage is axial planar to minor F_2 folds. The designation of the Hidden Lake synform as an F_2 structure creates a problem with respect to the missing F_2 anticline that should exist between the Hidden Lake synform and the F_2 Pipeline syncline. This remains an unresolved problem. The absence of an F_2 anticline could be due to the fact that the Hidden Lake synform and the Pipeline syncline are not coeval structures and therefore, a macroscopic F_2 anticline was never developed.

The peak metamorphic minerals identified during this study correspond to the isograds established by Digel and Gordon (Fig. 2.3; 1995) and are aligned within the S_2 cleavage. The isograds do not appear to be folded, suggesting that they postdate Hidden Lake synform development. This relationship corresponds with the interpretation that S_2 developed after the formation of this synform.

The dominant fold interference patterns observed within the field area formed as a result of interference between F_1 and F_2 folding and are transitional between type-I and type-II (Ramsay, 1967). The F_1 folds in the northern region of the study area had south-dipping axial planes and were overprinted by tight, west-verging, overturned F_2 folds with eastward-dipping axial planes. This overprinting produced a type-II geometry (Ramsay, 1967) which can be seen in the southeastern corner of the Pipeline interference structure. The axial planes of both the F_1 and F_2 folds in the southern part of the field area are generally more upright compared to those of folds in the north. D_2 deformation overturned the upright F_1 axial planes, producing overturned eastern limbs (with F_1 fold axes plunging steeply to the east) in both the Missi Outlier (Fig. 3.1) and the Mud Lake syncline. This resulted in a transitional type-I to type-II interference pattern (Ramsay, 1967).

In the northern field area, the fold axes of the F_1 , F_2 and F_3 structures are almost all coaxial, and also parallel with the mean attitude of the L_2 fabric (see Fig. 3.3, 3.4). The F_1 structures are inferred to be east-west trending folds that were deformed by north-trending F_2 folds. The parallel nature of most of the F_1 fold axes (e.g. Flin Flon Creek syncline and F_1 folds in core of Pipeline interference basin) with the F_2/L_2 linear fabric could suggest that the D_1 structures were rotated into alignment with the dominant D_2 linear fabric. The fold axes of the rarely developed F_3 structures are also coaxial to the D_2 linear fabric. The fact that the F_3 structures are not developed extensively throughout the field area suggests that the D_3 event is not responsible for the alignment of the F_1 and F_2 fold axes. Therefore, these relations

suggest that D_2 deformation could have re-aligned the earlier axes of the F_1 folds.

4.1.4 - D_3 and D_4 deformation

No macroscopic F_3 folds were observed within the study area. Isolated minor folds on the scale of 10 m or less were observed which deform stratigraphy and the S_2 cleavage. Within S_3 high-strain zones and in localities where the S_3 cleavage is well developed, the sedimentary clasts and volcanic fragments are re-aligned and flattened in this younger cleavage. These northwest-striking S_3 high-strain zones dissect the volcanic stratigraphy and show a variable amount of displacement. Two such zones occur on the northwest-trending segments of the Missi Wedge and overprint the D_1 Railway faults (Fig. 3.1). The D_3 high-strain zone on the eastern side of the Missi Wedge is interpreted as a normal fault that brought the younger Missi sedimentary rocks down relative to the Hidden Lake basalts. Based on cross-cutting relationships preserved north of the study area, the Cliff Lake fault is associated with this period of deformation.

D_4 deformation is characterized by brittle-ductile, oblique-slip, reverse faults that dissect the field area, offsetting all stratigraphic contacts and folds (Stockwell, 1960; Stauffer and Mukherjee, 1971, Bailes and Syme, 1989). Examples of these structures include the Ross Lake and Channing faults. A minimum age for deformation along the Ross Lake fault was calculated to be 1691 ± 6 Ma (K-feldspar, $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age, Fedorowich et al., 1995).

4.2 - Regional tectonic setting

Deformation recorded in the rocks within the study area can be related to events which occurred throughout the Flin Flon Belt and adjacent domains in the southeastern Trans-Hudson orogen (Table 2). Lucas et al. (1996) describe two regional events (D_1 and D_2) that predate deposition of the Missi Group, and with Ryan and Williams (1996), describe D_2 as a regional event resulting in a steepening of tectonostratigraphy throughout the Flin Flon Belt. The Burley Lake syncline provides evidence for a generation of folds predating deposition of the Missi Group within the study area (Stockwell, 1960; Bailes and Syme, 1996; this study).

The structural vergence during D_1 of this study (north-verging) differs significantly from the vergence associated with the correlative regional event (southwest-verging; D_{3a} : Lucas et al., 1996; Table 2). The timing of the D_1 event (this study) is constrained to occur between the emplacement of the Boundary Intrusions (ca. 1842 Ma., Heaman et al., 1992) and the onset of peak metamorphism (D_2 , this study: 1820-1790 Ma.; Fedorowich et al., 1995), and is therefore coeval with the D_{3a} event of Lucas et al. (1996). During this same time period, the Kiseynew Domain, comprising turbidites (Burntwood Group, Zwanzig 1990) which are the same age as the Missi Group (ca. 1840 Ma; David et al., 1996), was thrust southwestward over the Flin Flon Belt (Lewry et al., 1990; Connors, 1996).

Only a limited number of studies (Connors and Ansdell, 1994b; Kraus and Williams, 1994; Fedorowich et al., 1995; Connors, 1996) within the Flin Flon Belt

Lucas et al., 1996; Flin Flon terrane	Stauffer and Mukherjee, 1971; Missi Group	This study; Flin Flon arc assemblage and Missi Group
<p>D₁ Amalgamation of assemblages resulting in regional shear zones and creation of the Amisk Collage (1.88-1.87 Ga).</p> <p>D₂ Intrusion of plutons (1.86 to 1.84 Ga.), shear zones and formation of north-trending folds with an associated NNE-striking foliation.</p>		<p>D₁ N-NE-trending folds within Amisk Groups. Burley Lake syncline</p>

Missi	Group	Sedimentation
<p>D_{3a} Magmatism and thrusting of Kiseeynew Domain southward over the Amisk Collage. Collision of Reindeer Zone with the Saskatchewan craton (1.84-1.83 Ga.).</p> <p>D₃ Peak metamorphism and southwestward-thrusting of Reindeer Zone over the Saskatchewan Craton (1.83-1.80 Ga.).</p> <p>D₄ Formation of steeply-dipping shear zones, north-trending folds and associated foliations. Terminal collision with Superior Province (ca. 1.80-1.77 Ga.).</p> <p>D₅ Post-collisional structures: conjugate set of NNW-NNE-trending faults offsetting metamorphic isograds (1.77-1.69 Ga.).</p>	<p>P₁ Tightly-closed to isoclinal, V- to box-shaped folds. Axial planes vary due to refolding. FFCs and RCs.</p> <p>P₂ Tightly-closed, asymmetric, V- to box-shaped folds with well-developed axial planar foliation and lineation. Peak metamorphism (S₂)</p> <p>Not recognised</p> <p>P₃ NNW-trending faults. RLf and CLf.</p>	<p>D₁ N-NE-verging folds of Amisk and Missi Groups. Rare cleavage (S₁). FFCs, RLa, RCs and Missi Outlier.</p> <p>D₂ HLs. No cleavage.</p> <p>W-verging folds of Amisk and Missi Groups. Foliation (S₂) and lineation (L₂). MLs and Ps. Peak-metamorphism.</p> <p>D₃ Upright NW-trending folds. Spaced cleavage (S₃). CLf.</p> <p>D₄ NNW-trending, high-angle, oblique-slip faulting. RLf.</p>

Table 2. Summary of deformational events. FFCs: Flin Flon Creek syncline; RCs: Ross Creek syncline; RCa: Ross Lake anticline; MLs: Mud Lake syncline; Ps: Pipeline syncline; HLs: Hidden Lake synform; RLf: Ross Lake fault; CLf: Cliff Lake fault. Amisk Group = Flin Flon arc assemblage.

have recognized an early generation of post-Missi Group structures, pre-dating the peak metamorphic event at ca. 1820 Ma (David et al., 1996). Connors (1996) identified a generation of southwest-verging folds and faults in the File Lake area involving ca. 1840 Ma. Burntwood Group turbidites that are cross-cut by ca. 1830 Ma plutons (David et al., 1996). These relationships bracket deformation to between 1840 and 1830 Ma (Connors, 1996). The southwest vergence identified by Connors (1996) corresponds with the D_{3a} event of Lucas et al. (1996). While working in the southern flank of the Kiseynew Domain, Zwanzig (1995) identified an early set of thrusts and inferred, based on regional stratigraphic arguments, that the faults carried the older rocks of the Flin Flon Belt towards the north or east over the turbidites of the Kiseynew Domain. These early thrust faults are cut by the ca. 1830 Ma intrusions (David et al., 1996). If correct, Zwanzig's (1995) observations suggest that pre-peak metamorphic structures in the regional D_{3a} event (1840-1830 Ma) also include north- to east-verging structures. This is consistent with the north-verging structures (i.e., Railway faults, Club Lake fault, Flin Flon Creek syncline) documented in the Flin Flon area.

Observations from other orogenic belts can provide some insight as to how north-verging structures developed when, regionally, the Reindeer Zone (Trans-Hudson Orogen) was experiencing overall southwest-vergent deformation. Price (1986) discussed a number of kilometre-scale structures throughout the Canadian Cordillera which demonstrate opposing vergence. A model involving displacement of tectonic wedges, bounded above and below by thrust faults, was proposed to explain

this variation in vergence (Price, 1986). The Porcupine Creek anticlinorium is a complex fan structure that exhibits folds and faults with both northeast and southwest vergence (Price, 1986). This structure was created when a wedge of Proterozoic and Cambrian rocks were thrust eastward (Price, 1986). Comparisons can be made with the Flin Flon area where axial surfaces of F_1 folds vary (north to south) from moderately south-dipping to steeply north-dipping, and thus define a moderately-developed fan fold structure. These folds, along with the north-verging D_1 thrust faults (e.g. Club Lake structure), could have formed by processes similar to those described by Price (1986), during a time when the Reindeer Zone was undergoing southwestwardly-directed thrusting (Lewry, 1990; Connors, 1996; Lucas et al., 1996). More work is needed in this portion of the Flin Flon Belt to determine 1) if other north-verging structures exist, and 2) if a regional correlation can be made with the north- to east-verging structures observed by Zwanzig (1995) in the eastern Flin Flon Belt.

The local D_2 event produced west-verging folds (e.g., Hidden Lake synform, Pipeline syncline) during peak metamorphism. Regionally, the Trans-Hudson orogen was undergoing deformation and peak metamorphism (D_3b , Table 1; Lucas et al., 1996) during continued collision of the Flin Flon Belt with the Sask craton (Ansdell et al., 1995; Lucas et al., 1996). The D_3b event of Lucas et al. (1996) is marked by southwestwardly directed thrusting of the Kiseynew Domain over the older rocks of the Flin Flon Belt. Generally, the vergence occurring during the local D_2 event correlates with coinciding regional deformation (westerly as opposed to

southwesterly). The westward vergence of the local D_2 event could be explained by localized variations in vergence throughout the Flin Flon Belt.

The D_3 and D_4 events (this study) produced a generation of steeply-dipping, generally north-northwest- and northeast-trending, post-peak metamorphic folds and shear zones that are observed throughout the Flin Flon Belt (regional D_4 and D_5 ; Lucas et al., 1995). The northwest-trending, ductile to brittle faults recognized in this study can be separated into two generations of structures based on relationships with the Embury Lake antiform north of the study area (Fig. 2.2). The Cliff Lake fault is folded by this antiform and therefore this D_3 (local) structure can be correlated with the regional D_4 event (Table 2). The Ross Lake and Channing faults (D_4 , this study) offset both the Embury Lake antiform and the Cliff Lake fault and are correlative with the D_5 , regional, post-collisional deformation.

4.3 - Relationships of surface mapping to Callinan mine geology

Underground study has focused most recently on the Callinan deposit, resulting in a detailed structural summary for this area (Price, 1987, 1995). The following comparison between recent underground (Price, 1995) and surface (this study) structural models is based on reports provided by Hudson Bay Exploration and Development geologists. No work was completed by this author. It is important to note that interpretation of the underground structural data is difficult without a more detailed understanding of the respective foliation generation (S_1 , S_2 or S_3) throughout

each of the stopes.

D₁ folds and faults play a large role in controlling the distribution of the Mine horizon. As discussed above, a minimum of 2900 m of displacement (assuming northerly-directed vergence) along the generally south-dipping D₁ Club Lake structure has resulted in a structural overlap of Flin Flon arc assemblage on top of Missi Group sedimentary rocks. The layering within the Hidden Lake basalt sequence (and therefore the mine stratigraphy) on the western limb of the Hidden Lake synform dips moderately to the east or southeast. Based on these observations, the Club Lake structure must cut the east-dipping mine horizon at depth. A number of ore bodies within the mine horizon are located only slightly above the Club Lake structure (e.g. Four Queen's zone, 100-200 m structurally above the fault; Price, 1987).

Furthermore, the truncation of the mine horizon package at the Club Lake structure indicates that the continuation of mineralized horizons (e.g. Mine rhyolite) should be preserved in the footwall to the Club Lake structure. However, the net slip and net slip vector along the Club Lake structure are not well enough established (due to overprinting deformation) to predict where the footwall cut-off should occur.

Price (1995) summarized deformation from a number of stopes within the Callinan deposit and identified a fold that is overprinted by the pervasive foliation (S₂, this study). This isoclinal fold plunges 0° towards 327° and has a moderately northeast-dipping axial plane, suggesting that it could be an F₁ structure. Alternatively, this fold (which is only mapped underground) could be a pre-Missi Group structure, developed solely within the older volcanic rocks.

The second episode of deformation observed underground at Callinan is a pervasive flattening foliation with an associated lineation. The mean attitude of the flattened ore bodies (approximately striking 005° and dipping 45° east) is parallel to the mean flattening foliation that strikes north and dips moderately to the east (Price, 1995). A very strong mineral and/or stretching lineation (mean attitude plunging 34° towards 131°) is observed and is generally parallel to the mean attitude of the elongated ore bodies (plunging 37° towards 142°; Price, 1995). The S_2 and L_2 data from this study in the Hidden Lake synform area (Fig. 3.4) correspond to underground measurements. Therefore, it can be concluded that the D_2 event was largely responsible for the present geometry of the ore lenses. The mean S_2 from surface mapping (striking 027° and dipping 32° southeast) strikes more east of north and exhibits a shallower dip than that from underground. The pervasive S_2 foliation cross-cuts both limbs of the Hidden Lake synform at depth as it does on surface. Based on the macroscopic geometry of the Hidden Lake synform, all F_2 folds within the mine horizon should be southeast-plunging Z-folds.

The Flin Flon ore body is described as a proximal VMS deposit (Bailes and Syme, 1989), whereas the Callinan deposit is believed to have formed in a more distal environment (Price, 1995), away from the main volcanic vent. This is important because other distal ore bodies similar to Callinan might exist adjacent to the proximal Flin Flon vent. These distal ore bodies would presumably occur within the same stratigraphic horizon that is now folded by the D_2 Hidden Lake synform. These relationships are directly related to the Club Lake structure which extends southward

below this package of volcanic rocks (see Fig. 3.11). In areas only slightly south of the Club Lake structure, the mine horizon is truncated against the south-dipping basement-cover contact. In areas further to the south (X-X', Fig. 4.1, inside back cover) the mine horizon could extend around the Hidden Lake synform because the Club Lake structure is at significant depth. This relationship suggests that other distal ore bodies could be located on the eastern limb of the Hidden Lake synform.

A number of structures have been observed underground that post-date the S_2 pervasive foliation. Mapping in the 2512 stope at Callinan (Price, 1993) revealed two foliations (northeast striking, shallow dipping (S_2), and northwest striking, steeply dipping (S_3)) and identified both a northwest-striking high-strain zone that offset an ore lense to the east and a fold of the pervasive foliation with an axial plane parallel to the regional S_3 foliation. These observations are consistent with surface data; the foliations correspond to the S_2 and S_3 cleavage. Price (1995) also observed a number of large-scale folds at depth that deform the pervasive foliation about an east-plunging axes. These have apparently not yet been recognized at surface. The youngest deformation structures mapped underground consist of late brittle fractures, presumably correlating with D_4 deformation described at surface.

Bailes and Syme (1989) mapped a unit of felsic fragmental rocks north of Ross Lake and correlated them with the Railway volcanoclastic rocks that conformably overlie the Mine rhyolite on the western limb of the Hidden Lake synform. Thomas (1994) also identified similarities between the rocks north of Ross Lake and the Flin Flon-Callinan mine stratigraphy. Cross-section X-X' (Fig. 4.1, inside back cover)

was drawn to test the possibility that the rocks north of Ross Lake may be correlative with the mine stratigraphy. The Mine rhyolite (*sensu stricto*) is not presumed to be an extensive flow that is folded about the Hidden Lake synform. Instead, the possibility for the mine horizon being folded about the Hidden Lake synform was tested. The Club Lake structure reaches sufficient depth (as determined from drill holes) in this cross-section to allow for the mine horizon to be folded about the synform, as opposed to being truncated at the Club Lake structure. If it can be assumed that the mine horizon has a continuous, moderate eastward dip on the west limb of the Hidden Lake synform, then it should be folded about the Hidden Lake synform and truncated against the Ross Lake fault. The positioning of the Club Lake structure, the Little Cliff Lake fault and the displaced mine horizon in this cross-section was done using the fault plane map for the Ross Lake fault. The continuation of the mine horizon east of the Ross Lake fault is in close proximity to the felsic rocks north of Ross Lake. Therefore, based on this section, it is suggested that the felsic fragmental rocks north of Ross Lake could be stratigraphic equivalents to the Railway volcanoclastics.

4.4 - Advances made in this study

The following is a brief summary of the main advances made in this study towards the understanding of the structural geology surrounding Flin Flon, Manitoba.

This study documented the extent, character and variability of three cleavages

(S_1 , S_2 , S_3) and three fold generations (F_1 , F_2 and F_3), preserved in the Missi Group sedimentary cover sequence and the Flin Flon arc assemblage basement rocks. S_1/F_1 had not been observed within the Missi Outlier, and S_3/F_3 had not been extensively documented throughout the study area. These field observations were augmented by a microscopic examination of all the fabrics.

The variable nature of the contact between the basement and cover rocks was investigated during this study. The two outliers on the eastern limb of the Hidden Lake synform indicate an upright, unconformable basement-cover contact whereas to the north, along the Club Lake structure it is an overturned, sheared downward facing basement-cover contact. Based on the facing reversals at the basement-cover contact in the northern part of the study area, the F_1 Ross Lake anticline was identified south of the Club Lake structure. Similar relationships were observed at Sepple Hill where an overturned, sheared unconformity was recognized on the overturned limb of an F_1 fold. Based on these relations, it was concluded that D_1 thrusting is manifested on the overturned limbs of F_1 folds.

The basement-cover contact defining the Club Lake structure received particular focus during this study. Almost the entire 4 km length was interpreted as a thrust fault, but in Manitoba, where regolith is preserved in the hanging-wall volcanic rocks, the Club Lake structure was inferred to be a thrust fault developed at an overturned basement-cover contact.

Northward-directed kinematics for D_1 thrusting were concluded from F_1 fold vergence and limited L_1 fabric data. Using data from drill holes that intersected the

basement-cover contact at depth below the Hidden Lake synform, a minimum basement-on-cover overlap of 2900 m was calculated.

A fault plane map of the Ross Lake fault was constructed. This map suggested that the Club Lake structure continues on the east side of the Ross Lake fault as the Little Cliff Lake fault. The fault plane map also demonstrated that the Flin Flon Creek syncline does not correspond with the F_1 folds developed in the core of the Pipeline interference basin.

Some regions within the study area were re-interpreted. The southern closure of the Pipeline interference basin was previously interpreted to be an F_2 fold (Stauffer and Mukherjee, 1971). S_2 cleavage/bedding relationships suggest that this fold is an F_1 , and that the F_2 Pipeline syncline occurs farther to the west. Changes in stratigraphic facing directions, as indicated by cross-bedding in Missi Group sandstones, helped to recognize multiple F_1 folds in the core of the Pipeline interference basin.

As mentioned above, a number of F_3 folds were identified that deform the pervasive S_2 cleavage. High-strain zones associated with this event were interpreted to overprint earlier structures (e.g. Railway faults).

4.5 - Conclusions

Structures related to four periods of deformation were documented during this field study.

1) The first generation of structures is recognized solely within the Flin Flon arc assemblage basement rocks and provides evidence for deformation occurring prior to deposition of the Missi Group sedimentary cover sequence. These early folds are tight to isoclinal, north-trending structures with no observable cleavage. They are truncated at the basement-cover unconformity.

2) D_1 deformation followed emplacement of the Boundary Intrusions (ca. 1840 Ma.) and formed north-verging folds and thrusts in the northern study area, and upright to steeply south-dipping folds in the southern study area. The north-verging thrusts internally dissect the Flin Flon arc assemblage (e.g. Railway faults) and place volcanic basement rocks over sedimentary cover sequence (e.g. Club Lake structure). D_1 thrusts at the basement-cover contact developed on overturned, moderately south-dipping F_1 fold limbs, proving that F_1 folding predated D_1 thrusting. Decametric F_1 folds deforming the D_1 thrust foliation suggest that F_1 folding continued during thrusting. A very rare S_1 axial planar cleavage is developed, relative to the F_1 folds and an S_1 foliation is developed within each of the D_1 faults.

3) Drill hole data supplied by Hudson Bay Exploration and Development constrained the depth to the basement-cover contact below the centre of the Hidden Lake synform. Assuming north-verging kinematics for the D_1 Club Lake structure, 2900 m is estimated as the minimum displacement for basement-on-cover overlap.

- 4) The northerly directed vergence of D_1 structures is in contrast to the regional southwest-verging structures developed throughout the Flin Flon Belt (ca. 1840-1830 Ma). Structures showing opposing vergence are documented in other orogenic belts and are explained using a tectonic wedging model. The geometry shown by the D_1 structures within this study area could have formed during a similar process.
- 5) D_2 structures consist of closed to tight, west-verging overturned folds (e.g. Hidden Lake synform and Pipeline syncline) with a pervasive axial-planar cleavage (S_2). A well developed stretching lineation (L_2) is observed in the northern field area. An intermediate type-I to type-II fold interference pattern was created due to the F_2 folds overprinting the earlier F_1 folds.
- 6) Peak metamorphism (ca. 1820-1790 Ma) occurred during the D_2 event and produced metamorphic isograds ranging from middle greenschist facies to lower amphibolite facies conditions (south to north) within the study area. Thin sections indicate that peak metamorphic minerals are aligned in the S_2 fabric and that the rocks in the northern study area are $L > S$ tectonites (i.e. deformed by prolate strain).
- 7) D_3 structures are characterized by rare, upright, northwest-striking open folds with an axial planar cleavage (S_3), and by steeply northeast-dipping shear zones (e.g. Cliff Lake fault) that dissect basement and cover rocks. Kinematics along these structures are variable, showing both sinistral oblique-slip thrusting (e.g. Cliff Lake fault) and

normal faulting (eastern Missi Wedge).

8) D_4 structures consist of steeply northeast-dipping, oblique-slip, brittle-ductile thrust faults (e.g. Ross Lake fault) that offset all earlier structures.

9) Construction of a fault plane map of the Ross Lake fault permitted the correlation of the Club Lake structure with the Little Cliff Lake fault. This map also demonstrated that the continuation of the F_1 Flin Flon Creek syncline in the hanging wall of the Ross Lake fault does not lie in the core of the Pipeline syncline, but instead, is located to the north.

9) The nature of the contact between the Flin Flon arc assemblage is variable throughout the study area. In most of the southern regions, the basement-cover contact is a well preserved unconformity, with regolithic material in the volcanic rocks and a conglomerate in the Missi Group. In the northern area, the basement-cover contact is dominantly a thrust fault that developed along an overturned limb of an F_1 fold (e.g. Club Lake structure, Manitoba).

4.5 - Recommendations for further study

A number of issues discussed in this thesis could be re-examined during further studies within the Flin Flon area.

More mapping could be completed in the Sepple Hill area to look for evidence of the inferred F_1 fold which overturned the basement-cover contact prior to D_1 thrusting.

The relationships between peak metamorphic mineral growth and the S_1 shear zone fabric (e.g. Club Lake structure, Railway faults) could be addressed by obtaining more samples from these D_1 zones. Also, obtaining a greater density of samples from within the core of the Hidden Lake synform area could test the interpretation by Digel and Gordon (1995) that the isograds are not folded by the Hidden Lake synform.

Sections along the Club Lake structure where a preserved unconformity exists could be re-examined to test the interpretation of the Club Lake structure branching away from the basement-cover contact, and thrusting Missi Group on Missi Group.

And finally, a regional examination of the Flin Flon area could be carried out to compare and contrast the geometry of other structures formed during the D_1 event (this study; 1840-1820 Ma).

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PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

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Black and white photographic prints (17" x 23") are available for an additional charge.

UMI

Cross Section W-W'

400 m

Cross Section Y-Y'

400 m

Cross Section X-X'

400 m

Cross Section Z-Z'

Figure 4.1. Locations of four schematic vertical cross-sections are shown. The Miss Group sedimentary basin is positioned by extending the dip of the plane of section (sections W-W' and Z-Z'). Section X-X' is folded about the Hidden Lake synform and offset by the Ross Lake fault.

tical cross-sections are shown on Map 1 and Map 2, inside back cover. Depth to base of Missi
ned by extending the dip of the unconformity exposed 2 km northeast of Flin Flon Lake into the
and Z-Z'). Section X-X' is slightly interpretive but shows the Flin Flon-Callinan mine horizon
nform and offset by the Ross Lake fault.

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Oversize maps and charts are filmed in sections in the following manner:

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UMI

MAP 1: GEOLOGY OF THE NORTHERN LEGEND

Approximate mean declination 1989
Annual change decreasing 23.0'

1:5000

Intrusives

Cliff Lake Granite:

Oligoclase granite characterized by large eyes of bluish quartz.

Felsic dykes:

Aphyric dacitic to rhyolite dykes; feldspar-phyric porphyrys.

Boundary Intrusions:

Hornblende- and pyroxene-phyric gabbro, with minor diorite.

Limit of mapping

Club Lake structure

*Footwall Volcaniclastics
and
Club Lake Felsic Eruptive Unit*

*Flin Flon
Lake*

NORTHERN FLIN FLON AREA

1:5000

500 metres

Lakes

Outcrop

Provincial border

Airstrip

Water pipeline

Highways

Roads

F3 axial trace

large

dispar-

bbro,

*Little
Cliff
Lake*

Cliff Lake Granite:

Oligoclase granite characterized by large eyes of bluish quartz.

Felsic dykes:

Aphyric dacitic to rhyolite dykes; feldspar-phyric porphyrys.

Boundary Intrusions:

Hornblende- and pyroxene-phyric gabbro, with minor diorite.

Missi Group

Cliff Member

Sandstone

Sandstone with minor pebbles.

Pebbly sandstone

Sandstone with 5-15 % pebbles.

Conglomerate

Pebble to cobble conglomerate.

Beaverdam Member

Sandstone:

Sandstone with minor pebbles. Isolated beds of conglomerate.

Pebbly sandstone:

Sandstone with 5-15% pebbles.

Conglomerate:

Pebble to cobble conglomerate.

Flin Flon arc assemblage

Andesitic flow:

Feldspar-phyric pillowed and massive flows with flow top amoeboid pillow breccia.

Louis Lake basalts:

Feldspar- and pyroxene-phyric, pillowed and massive mafic flows.

6

Felsic flow:

Feldspar-phyric dacitic to rhyolitic flows.

5

Felsic tuff:

Mafic monolithologic felsic tuff breccia. Rhyolite fragments are average 6-7 cm; sparsely quartz-phyric and moderately feldspar-phyric.

Mafic tuff:

Mafic ash to lapilli tuff; average fragments 1-2 cm diameter.

Hidden Lake basalt:

Aphyric- to feldspar-phyric pillowed mafic flows with flow top amoeboid pillow breccia; minor massive flows.

Mine package:

Mixed mafic and felsic flows, and tuffs. Host to all mineralization (note: location of unit taken from HBED maps).

Mafic tuff:

Mafic heterolithologic lapilli tuff to tuff breccia. Fragments are average 3-4 cm in diameter.

by large
s; feldspar-
ic gabbro,

es.

Isolated

s.

assive flows
breccia.

pillowed and

olitic flows.

breccia. Rhyolite
n; sparsely
feldspar-phyrlic.

le fragments

llowed mafic
pillow breccia;

nd tuffs.
t location of

to tuff breccia.
n in diameter.

Water pipeline

Highways

Roads

F3 axial trace

F2 axial trace

F1 axial trace

Fault: assumed

Fault: approximate

Fault: defined

Reverse fault

Thrust fault

Assumed contact

Known contact

Syncline; synform; overturned syncline

Anticline; antiform; overturned anticline

S-fold axis
generation: 1st, 2nd, 3rd

Z-fold axis
generation: 1st, 2nd, 3rd

Fold axis
generation: 1st, 2nd, 3rd

Lineation
generation: 1st, 2nd, 3rd

Axial plane
generation: 1st, 2nd, 3rd

Foliation
generation: 1st, 2nd, 3rd

Flow contact
top: unknown, known, overturned

Pillowed flow
top: unknown, known, overturned

Bedding
top: unknown, known, overturned

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Limit of mapping

Ross

Lake

PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

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MAIN
SHAFT

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Limit of mapping

316000

Ross

Lake

Lake

Limit of mapping

72

318000

Limit of mapping

6702000

Cliff

73

MAP 2: GEOLOGY OF THE SOUTHERN LEGEND

Approximate mean declination 1989
Annual change decreasing 23.0'

1:5000

Intrusives

Cliff Lake Granite:

Oligoclase granite characterized by large eyes of bluish quartz.

Felsic dykes:

Aphyric dacitic to rhyolite dykes; feldspar-phyric porphyrys.

Boundary Intrusions:

Hornblende- and pyroxene-phyric gabbro, with minor diorite.

Missi Group

Member

Sandstone

Sandstone with minor pebbles.

Cliff

Pebbly sandstone

Sandstone with 5-15 % pebbles.

Little

Conglomerate

Pebble to cobble conglomerate.

Member

Sandstone:

Sandstone with minor pebbles. Isolated

SOUTHERN FLIN FLON AREA

ND

1:5000

500 metres

Lakes

Outcrop

Provincial border

Airstrip

Water pipeline

Highways

Roads

F3 axial trace

F2 axial trace

F1 axial trace

Fault: assumed

Fault: approximate

Fault: defined

Reverse fault

Thrust fault

Assumed contact

by large

feldspar-

gabbro,

Isolated

Louis

Lake

Mud

Lake

between

the

6702000

Cliff Lake fault

Y'

*Mud
Lake*

10

with minor diorite.

Missi Group

Little Cliff Member

Sandstone

Sandstone with minor pebbles.

Pebbly sandstone

Sandstone with 5–15 % pebbles.

Conglomerate

Pebble to cobble conglomerate.

Beaverdam Member

Sandstone:

Sandstone with minor pebbles. Isolated beds of conglomerate.

Pebbly sandstone:

Sandstone with 5–15 % pebbles.

Conglomerate:

Pebble to cobble conglomerate.

Flin Flon arc assemblage

Andesitic flow:

Feldspar–phyric pillowed and massive flows with flow top amoeboid pillow breccia.

Louis Lake basalts:

Feldspar– and pyroxene–phyric, pillowed and massive mafic flows.

Felsic flow:

Feldspar–phyric dacitic to rhyolitic flows.

Felsic tuff:

Mafic monolithologic felsic tuff breccia. Rhyolite fragments are average 6–7 cm; sparsely quartz–phyric and moderately feldspar–phyric.

Mafic tuff:

Mafic ash to lapilli tuff; average fragments 1–2 cm diameter.

Hidden Lake basalt:

Aphyric– to feldspar–phyric pillowed mafic flows with flow top amoeboid pillow breccia; minor massive flows.

Mine package:

Mixed mafic and felsic flows, and tuffs. Host to all mineralization (note: location of unit taken from HBED maps).

Mafic tuff:

Mafic heterolithologic lapilli tuff to tuff breccia. Fragments are average 3–4 cm in diameter.

Syncline; synform; overturned syncline

Anticline; antiform; overturned anticline

S-fold axis
generation: 1st, 2nd, 3rd

Z-fold axis
generation: 1st, 2nd, 3rd

Fold axis
generation: 1st, 2nd, 3rd

Lineation
generation: 1st, 2nd, 3rd

Axial plane
generation: 1st, 2nd, 3rd

Foliation
generation: 1st, 2nd, 3rd

Flow contact
top: unknown, known, overturned

Pillowed flow
top: unknown, known, overturned

Bedding
top: unknown, known, overturned

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flows

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*Northwest Arm
Schist Lake*

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GALE, DAVID FRANCIS GILBERT
MQ20640
FIGURE 4.1

Figure 4.1 Locations of four schematic vertical cross-sections are shown on Map 1 and Map 2, inside back cover. Depth to base of Missi Group sedimentary basin postulated by extending the dip of the unconformity exposed 2 km northeast of Flin Flon Lake into the plane of section (sections W-W' and Z-Z'). Section X-X' is slightly interpretive but shows the Flin Flon-Callinan mine horizon folded about the Hidden Lake syncline and offset by the Ross Lake fault.