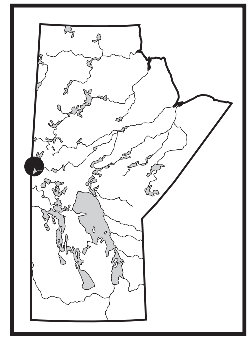
GS-1 Implications of new geological mapping, geochemistry and Sm-Nd isotope data, Flin Flon area, Manitoba (part of NTS 63K12)

by R-L. Simard and R.A. Creaser[1]



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Summary

Over the last two years, the rocks of the Flin Flon area have been the focus of a new 1:5000 scale bedrock mapping campaign aiming at the production of a new 1:10 000 scale stratigraphically coherent cross-border geological map, as part of the federal Targeted Geoscience Initiative (TGI-3). Using a combination of detailed volcanic facies analysis, structural mapping and thorough geochemical characterization of each unit in the area, this mapping campaign has allowed the recently established Flin Flon–Callinan–Triple 7 mine stratigraphy to be extended away from the main mines area south to Schist Lake.

Rocks west of the Mandy Road Fault in the Schist Lake–Mandy mines area, approximately 5 km south of Flin Flon, are mainly juvenile tholeiitic, aphyric and pyroxene-plagioclase–phyric basaltic flows with a lesser amount of plagioclase-crystal–rich heterolithic mafic breccia. These rocks are most similar to those in the Hidden and Louis formation rocks, the hangingwall rocks of the Flin Flon–Callinan–Triple 7 mine. Rocks east of the Mandy Road fault, however, are heterolithic mafic breccia (not plagioclase-crystal rich) with minor aphyric basaltic flows and host the Schist Lake and Mandy volcanogenic massive sulphide (VMS) deposits. These rocks appear to be different from both the footwall and the hangingwall rocks of the Flin Flon–Callinan–Triple 7 mines.

Mapping of the main structural elements in the Hidden Lake area, just south of the CN Rail line in the main Flin Flon–Callinan–Triple 7 mine stratigraphy, has highlighted a need for further work in that domain. Although individual structures such as the Hidden Lake syncline, the Railway Faults, the Missi wedge structure and the Ross Lake Fault can be readily documented, their relative timing is not satisfactorily resolved.

Introduction

The Flin Flon area of the Paleoproterozoic Flin Flon Belt is well known for its volcanogenic massive sulphide (VMS) deposits. Three active (Callinan, Triple 7 and Trout Lake) and three past-producing (Flin Flon, Mandy and Schist Lake) VMS mines occur in the immediate vicinity of the town of Flin Flon, which makes this area one of the most productive base-metal regions in Canada.

With the intent of stimulating private-sector resource exploration in areas of high base-metal potential in established mining communities, the Government of Canada launched a new five-year Targeted Geoscience Initiative (TGI-3) in 2005. As part of this initiative, the Manitoba Geological Survey, in collaboration with the Saskatchewan Geological Survey, the Geological Survey of Canada and researchers from Laurentian University, is participating in the production of a new 1:10 000 scale coherent stratigraphic cross-border geological map of the Flin Flon area.

This report summarizes observations and data collected during the final twelve-week field program of 1:5000 scale bedrock geological mapping in the Flin Flon area during the summer of 2007. In addition, it includes new geochemical and isotopic results from last year's mapping in the area. The field and analytical studies in this area are intended to characterize and differentiate the various volcanic sequences, provide constraints on their distribution and assess their stratigraphic position relative to those hosting the VMS deposits at Flin Flon.

Regional setting

The Paleoproterozoic Flin Flon Belt is part of the Reindeer Zone of the Trans-Hudson Orogen (Figure GS-1-1). The Flin Flon Belt consists of a series of tectonostratigraphic assemblages (juvenile arc, juvenile ocean-floor backarc, ocean plateau, oceanic-island basalt and evolved plutonic arc) that range in age from 1.92 to 1.87 Ga (Syme et al., 1999). All of the VMS deposits mined to date in the Flin Flon area are associated with the 1.9 Ga juvenile Flin Flon arc assemblage (Syme et al., 1999).

Volcanic rocks of the Flin Flon arc assemblage mainly consist of tholeiitic subaqueous pillowed basalt and basaltic andesite, with lesser amounts of heterolithic mafic breccia and mafic and felsic volcaniclastic rocks, and minor dacitic to rhyolitic flows (Bailes and Syme, 1989). Within the dominantly mafic volcanic complex at Flin Flon, the VMS deposits are spatially linked to felsic volcanic units that occur in synvolcanic collapse structures and calderas (Bailes and Syme, 1989; Syme and Bailes, 1993; Figure GS-1-2).

Bedrock geology of the Flin Flon area

Exposure in the Flin Flon area is exceptional, with

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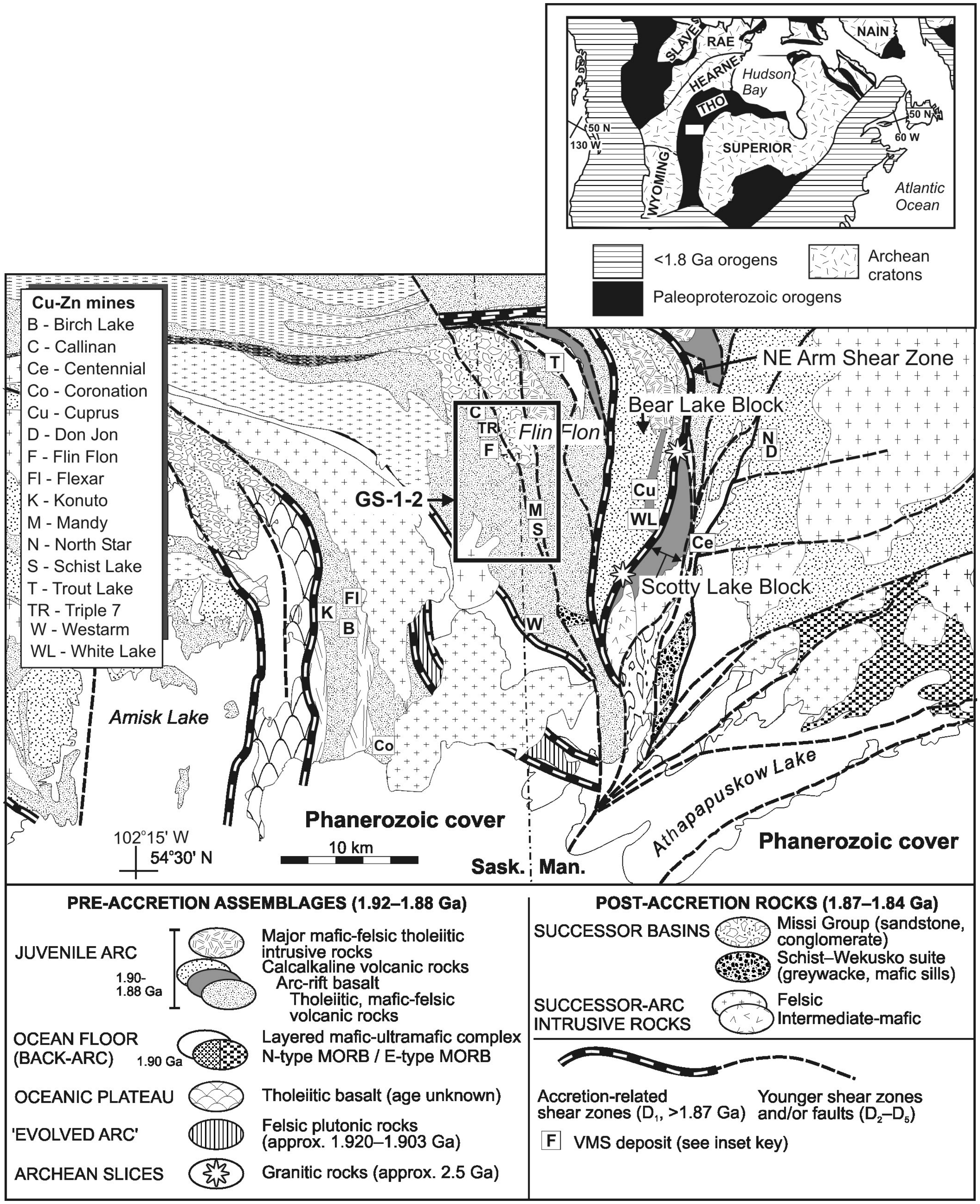

Figure GS-1-1: *Geology of the Flin Flon Belt, showing locations of known volcanogenic massive sulphide (VMS) deposits (*modified from *Syme et al., 1999); box indicates the area covered by Figure GS-1-2; inset map shows the location of the Flin Flon Belt within the Trans-Hudson Orogen (THO).*

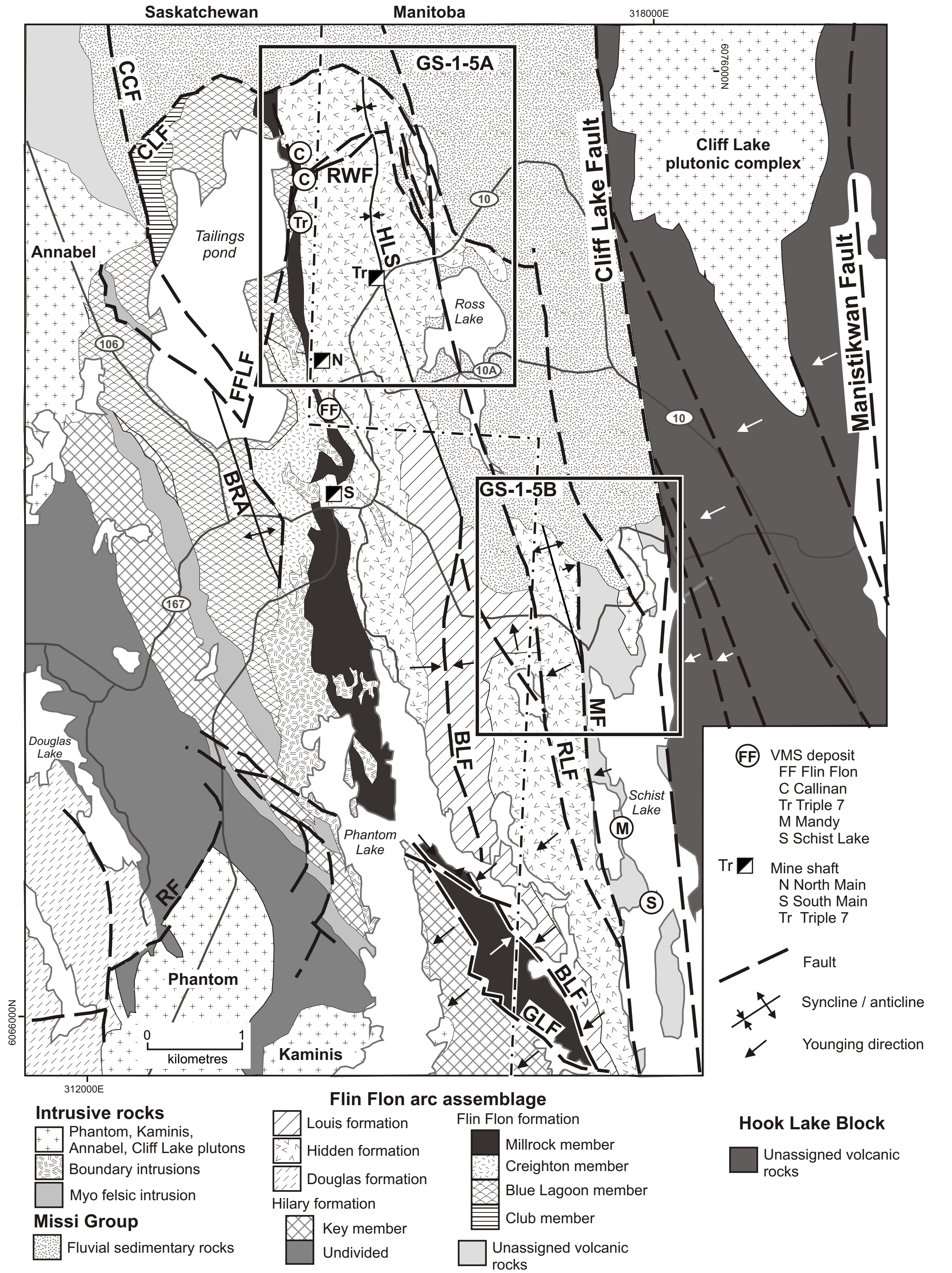

Figure GS-1-2: *Simplified geology of the Flin Flon area, showing major structures; boxes indicate the area covered by recent 1:5000 bedrock mapping. Abbreviations: BLF, Burley Lake Fault; BRA, Beaver Road anticline; CCF, Creighton Creek Fault; CLF, Club Lake Fault; FFLF, Flin Flon Lake Fault; GLF, Green Lake Fault; HLS, Hidden Lake syncline; MF, Mandy Road Fault; RF, Rio Fault; RLF, Ross Lake Fault; RWF, Railway Fault.*

commonly 40–80% lichen-free outcrop. Regional metamorphism is lower-greenschist facies (epidote-chlorite; Bailes and Syme, 1989), with good preservation of primary textures. The extent of recent Manitoba Geological Survey (MGS) 1:5000 scale bedrock mapping in the Flin Flon area, which is discussed in this report, is shown in Figure GS-1-2.

Geological mapping and stratigraphic analysis of volcanic rocks of the Flin Flon mines area (Devine, 2003; Tardif, 2003; DeWolfe and Gibson, 2005, 2006; Gibson, unpublished data, 2000–2006) have established an informal stratigraphic subdivision of rocks occurring in the footwall, along strike and in the hangingwall of the Flin Flon, Callinan and Triple 7 massive sulphide deposits (Devine, 2003; DeWolfe and Gibson, 2005, 2006). Figure GS-1-3 summarizes this informal stratigraphy for the mine area and for equivalent rocks to the south in the Schist Lake–Mandy mines area (Simard, 2006a).

Mapping this past summer focused in three areas: 1) the Hidden Lake area, 2) the Mandy Road–Channing area, and 3) the Hook Lake block. The first two areas are discussed in this report and the third area in a separate report (Kremer and Simard, GS-2, this volume).

Hidden Lake area

Stratigraphy

The 1:5000 scale mapping in the Hidden Lake area in 2007 was focused south of the CN Rail line, in an area not previously covered by 1:2000 mapping by Y.M. DeWolfe (Figure GS-1-2; DeWolfe, 2007a–e). As previously described by DeWolfe and Gibson (2005, 2006), rocks in this area are mainly basaltic flows and intrusions with minor interflow tuff and volcaniclastic rocks. They belong to the Hidden formation, which is composed of the Reservoir member, a thick suite of aphyric, plagioclase-phyric and minor plagioclase-pyroxene–phyric mafic flows and sills with minor intercalated mafic tuff; the Stockwell member, a more localized strongly plagioclase-phyric series of basaltic flows with minor associated mafic volcaniclastic rocks; and the 1920 unit, a very localized andesitic cryptoflow of icelanditic composition (DeWolfe and Gibson, 2005, 2006). The latter two members occur in the thrust panels north of the CN Rail line.

The observed stratigraphy on the west limb and in the nose of the Hidden Lake syncline south of the CN Rail line is a sequence of aphyric, plagioclase-phyric

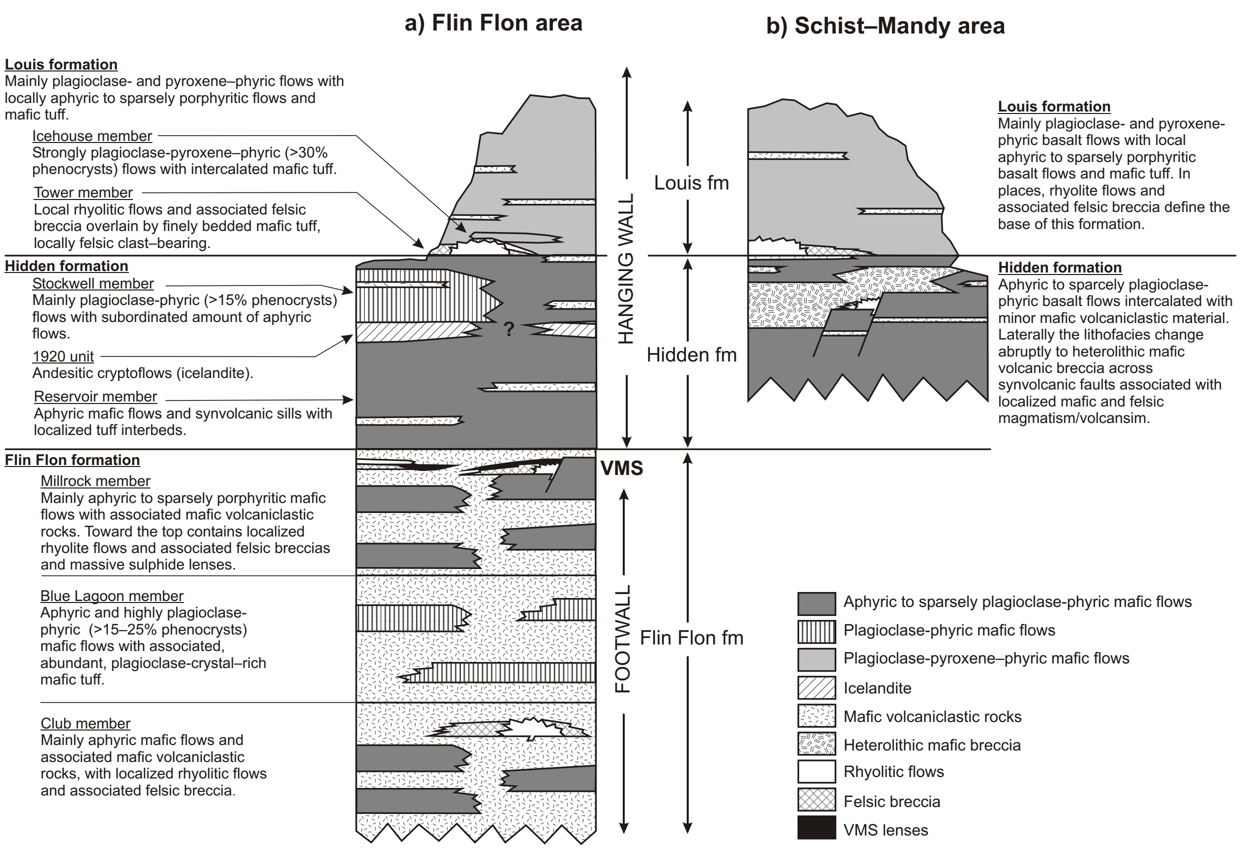

Figure GS-1-3: *Schematic stratigraphic section of the Flin Flon area:* ***a)*** *Flin Flon area schematic stratigraphy (*modified from *Devine, 2003; DeWolfe and Gibson, 2006);* ***b)*** *Schist Lake–Mandy mines area schematic stratigraphy (Simard, 2006a).*

and pyroxene-plagioclase–phyric pillowed and massive basaltic flows greater than 800 m thick (Simard et al., 2007). Conversely, the stratigraphy of the east limb of the Hidden Lake syncline in that same area is less than 300 m thick and composed almost entirely of plagioclase-phyric pillowed flows. All these rocks are part of the Reservoir member of the Hidden formation (DeWolfe and Gibson, 2006).

The aphyric flows in the area usually weather black and are dark green on fresh surfaces. The flows are generally aphyric to sparsely plagioclase phyric, with less than 2% plagioclase phenocrysts (<2 mm), and are generally 2–75 m thick, averaging 5–15 m (Figure GS-1-4a). The thicker massive flows have a medium- to coarse-grained base with ~2–5% amygdules (2–4 mm in diameter) appearing toward the middle; some show columnar jointing toward the base (Figure GS-1-4b). The amygdules slowly increase in size toward the top of the flows, where they can form gas cavities up to 5 cm in diameter. Massive flows are usually overlain by large (60–200 cm in diameter), closely packed, highly amygdaloidal (15–20%, 2–5 mm in diameter, quartz-filled) pillows showing thick (up to 2 cm), negatively weathered chilled margins.

The plagioclase-phyric flows usually weather buff brown and are dark green on fresh surfaces. The flows generally show 5–20% plagioclase phenocrysts (2–3 mm in diameter) and greatly vary in thickness. Plagioclase-phyric flows are usually pillowed (showing pillows 50–120 cm in diameter), amygdaloidal (20–25%, 2–3 mm in diameter, quartz-filled) and closely packed (Figure GS-1-4b). The pillows usually display a thin (1.5 cm thick) chilled margin with varying amounts (5–15%) of fine-grained interpillow tuffaceous material.

The plagioclase-pyroxene–phyric flows usually weather buff brown and are dark green on fresh surfaces. The flows generally have 10–15% plagioclase phenocrysts (2-3 mm in diameter) and approximately 10% pyroxene phenocrysts (1-4 mm in diameter), and are 1–20 m thick. Most flows are massive to pillowed and quartz amygdaloidal (5–15%, 23 mm in diameter), have small pillows 15–60 cm in diameter and are surrounded by up to 25% fine-grained interpillow material. The plagioclase-pyroxene–phyric flows, which comprise only 5% of the overall Hidden formation stratigraphy, are localized on the west limb of the Hidden Lake syncline.

A minor amount of mafic tuffaceous rocks can be found in the area. They form either a very thin veneer of very fine grained, well-bedded mafic tuff atop flows (Figure GS-1-4d) or localized, 1–5 m thick, laterally discontinuous, massive to well-bedded mafic lapilli tuff and tuff layers (Figure GS-1-4e).

Volcanic rocks in the Hidden Lake area are crosscut by numerous mafic dikes (aphyric, plagioclase phyric, plagioclase-pyroxene phyric and gabbroic), generally trending north to northwest. These mafic dikes are 0.3–3 m wide and can generally be followed over tens of metres in length. Fewer felsic dikes (aphyric and quartz-plagioclase phyric) are observed in the area. Their orientations seem random and they are more often found in proximity to shear zones.

Structure

Four major structural elements are present in the Hidden Lake area: 1) major curvilinear north-northeast– to east-trending Railway Fault(s), 2) the Hidden Lake syncline, 3) the Missi wedge structure and 4) the late north-northwest–trending strike-slip Ross Lake Fault (Figure GS-1-2, -5). The relative timing of these different structural events, with the exception of the late timing of the Ross Lake Fault, is currently unresolved to the satisfaction of geologists working in the area. The objective of the 2007 structural mapping program was to systematically document the distribution of the various foliations, lineations and shear zones in the area, in order to better understand the sequence of structural events in the area.

Upper and Lower Railway faults

The Upper and Lower Railway faults, which are locally exposed along the CN Rail line north of Hidden Lake (Figures GS-1-2, -5), are the most prominent of a set of bedding-parallel shear zones within the Hidden formation (Stockwell, 1960; Bailes and Syme, 1989; Thomas 1992; Gale et al., 1999). They form centimetre- to metre-wide dextrally reactivated ductile shear zones, with relict kinematic indicators (C/S fabrics) consistent with northward-thrusting movement along these structures (Fedorowitch et al., 1995; Gale, 1997). They also coincide with a prominent north-south break, from a high magnetic signature to the north, to low magnetic signature to the south, on the regional magnetic survey. Previous and recent mapping clearly document that they structurally juxtapose distinct portions of the Hidden formation stratigraphy on the west limb of the Hidden Lake syncline (Figure GS-1-2; DeWolfe and Gibson, 2006; DeWolfe, 2007a–c; Simard et al., 2007).

A thin package (~125 m thick) of aphyric and plagioclase-phyric basaltic flows trending approximately 020° and facing to the southeast occurs immediately south of the CN Rail line. This package extends east, close to the nose of the Hidden Lake syncline, but cannot be followed any farther (Figures GS-1-2, -5). The base of this package is not exposed anywhere to the north (CN tracks). Previous mapping has clearly shown that the rocks immediately to the north of the tracks are clearly different; the Upper Railway Fault is interpreted to separate the two packages (Figures GS-1-2, -5; Stockwell, 1960; Bailes and Syme, 1989; DeWolfe, 2007a, b).

Rocks immediately to the south of this thin package of flows consist of a very thick package (>800 m) of aphyric, plagioclase-phyric and minor plagioclase-pyroxene–phyric basaltic flows trending approximately 045° and facing to the southeast. The base of this southern

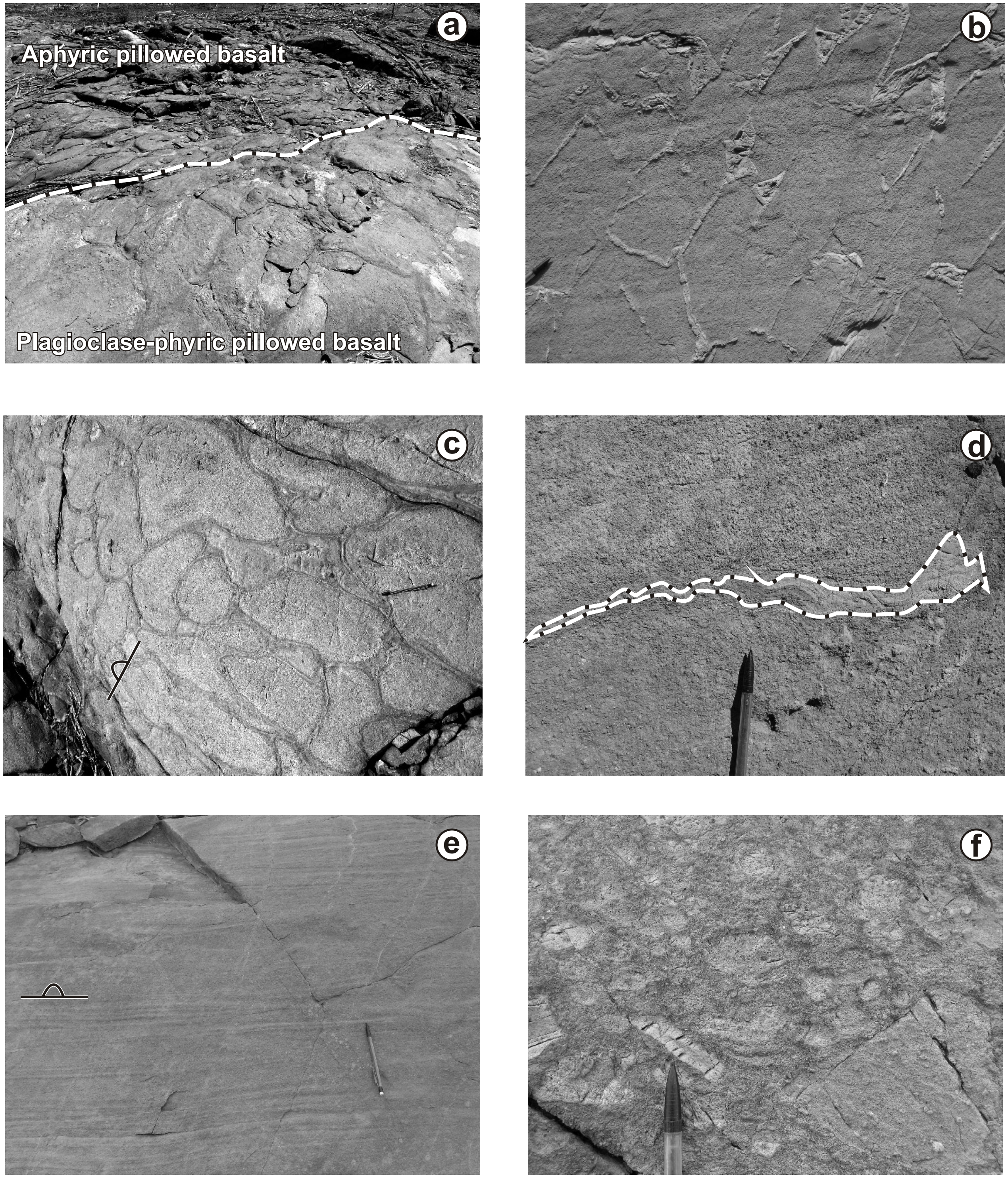

Figure GS-1-4: Photographs of various volcanic rocks of the Hidden formation: ***a)*** *contact between plagioclase-phyric pillowed flows (light coloured) and aphyric pillowed flows (dark coloured); photograph 10 m wide;* ***b)*** *columnar jointing at the base of a massive aphyric flow; tip of pen for scale;* ***c)*** *closely packed plagioclase-phyric pillowed flows; symbol indicates stratigraphic top;* ***d)*** *very fine grained, well-bedded mafic tuff atop massive basaltic flows; pen for scale;* ***e)*** *laterally discontinuous, massive to well-bedded mafic lapilli tuff; symbol indicates stratigraphic top; pen for scale;* ***f)*** *plagioclase-crystal–rich heterolithic mafic breccia showing mainly amygdaloidal aphyric basaltic clasts with a few angular tuffaceous clasts; pen for scale.*

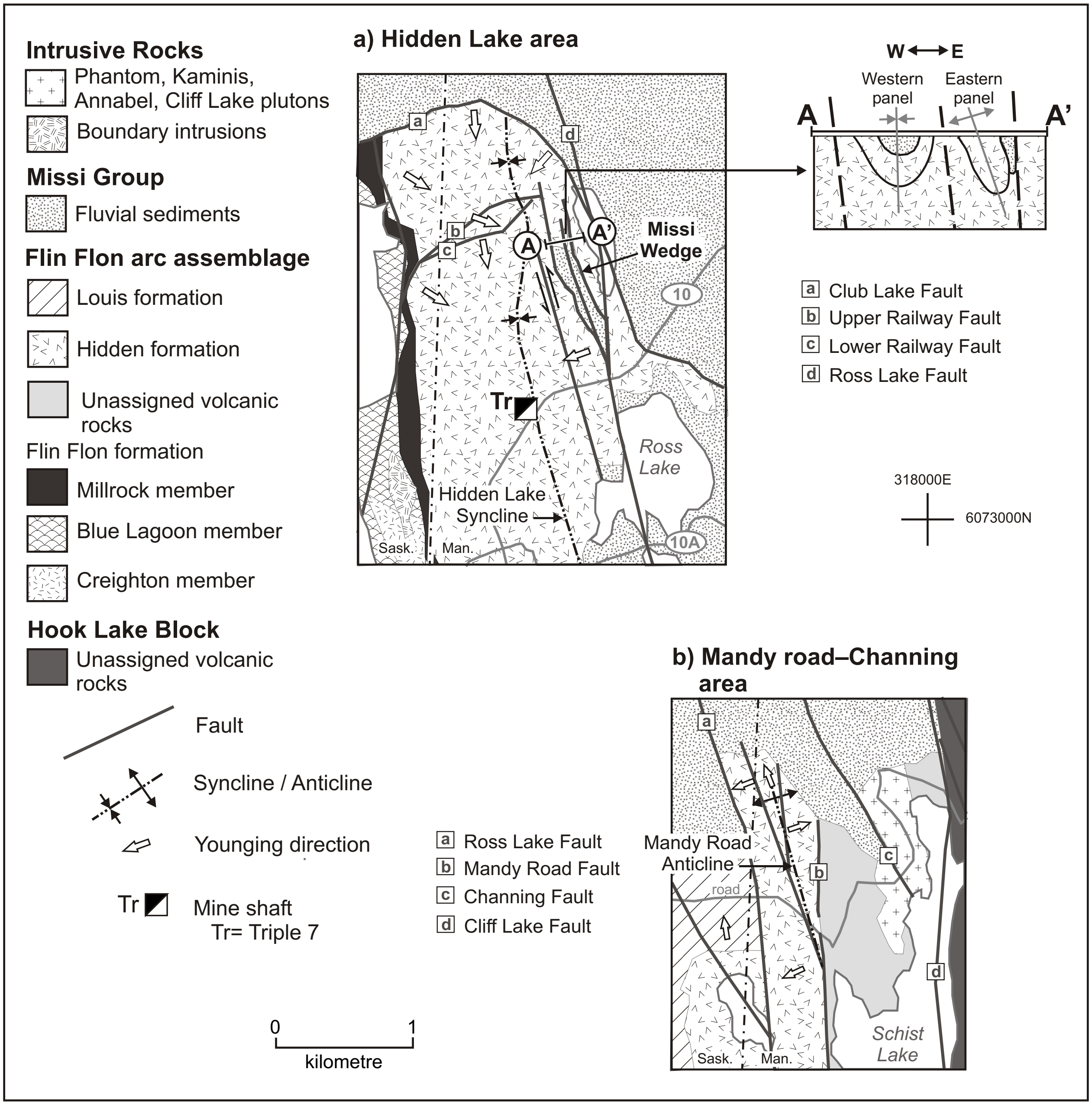

Figure GS-1-5: *Close-up of the **a)** Hidden Lake area, and **b)** Mandy Road–Channing area, outlining various structural elements.*

package is exposed in a cliff overhanging a small swampy valley between the two packages. The exposure displays a few dextral shear zones that are approximately 2 m wide, shallowly south-dipping and/or bedding-parallel and trending approximately 030°. These shear zones are interpreted to be the dextrally reactivated Lower Railway Fault (Figure GS-1-5a). The Lower Railway Fault is interpreted to be the base of this southern package of rock, which can be followed to the nose of the Hidden Lake syncline to the northeast, where it joins with the Upper Railway Fault (Figure GS-1-5a).

The eastern extensions of the Railway Faults have traditionally been portrayed as curving into the bounding faults of the Missi wedge structure (Stockwell, 1960; Bailes and Syme, 1989). Recent mapping, however, shows that the Missi wedge stratigraphy extends at least 100 m north of the CN Rail line (*see* details below; Simard et al., 2007; Hudson Bay Exploration and Development Co. Ltd., unpublished map). This suggests that the Railway Faults are truncated by the Missi wedge north-northwest–trending bounding shear zones (Figure GS-1-2), as was previously proposed by Gale (1997).

Hidden Lake syncline

The location of the Hidden Lake syncline south of the CN Rail line is facilitated by the high quality of exposure and good preservation of the volcanic flow internal structures. A north-northeast–trending east-southeast–facing succession of thick basaltic flows of the Reservoir member characterizes the west limb of the Hidden Lake syncline (Figure GS-1-5a). To the north, these flows gradually become east trending as the nose of the fold is approached. Rocks on the eastern limb of the syncline consist of a much thinner, slightly overturned north-northwest–trending, south-southwest–facing uniform succession of closely packed plagioclase-phyric basaltic flows, which are cut by the north-northwest–trending Missi wedge structures to the east (Figure GS-1-5a).

A relatively thin (~1–2 m thick) but laterally continuous, sinistral, south-southeast–trending shear zone occurs approximately 100 m east of the Hidden Lake syncline nose (Figure GS-1-5a). This shear zone, which can be followed south to Ross Lake and traced into an anastomosing system, is located exactly at the break in stratigraphy between the thick western limb and nose of the Hidden Lake syncline, and its thin eastern limb. It is also located exactly where a sharp break in the flow-facing direction occurs from the thick east-west flows in the nose of the fold to the west, and the south-southeast–trending thinner flows to the east (eastern limb of the syncline).

Volcanic rocks in the Hidden Lake area always display two distinct foliations: an early steeply dipping foliation trending approximately 345–350°, which is overprinted by a late shallowly dipping foliation that is trending 015°. North and east of the CN Rail line, the rocks of the east limb of the Hidden Lake syncline are much more deformed than those on the west limb. There they display a very strong, late, moderately dipping overprinting foliation that trends ~355°, parallel to the Ross Lake Fault to the east (Figure GS-1-5a).

A somewhat prominent stretching lineation, moderately plunging at 145–155°, is preserved as elongated amygdules and pillows (1:3–1:10 ratios) throughout the Hidden Lake area. This lineation is particularly prominent in the core of the Hidden Lake syncline southeast of Reservoir Lake.

Missi wedge structure

Recent mapping in the area of the Missi wedge structure has resulted in a better understanding of the internal stratigraphy of the wedge, and therefore its internal structure. The Missi wedge structure is composed of a series of narrow, fault-bounded wedges of both mafic volcanic (Hidden formation?) and fluvial sedimentary (Missi Group) rocks. They occur within the east limb of the Hidden syncline between a set of sinistrally reactivated, north-northwest–trending tear faults (Figures GS-1-2, -5b).

The Missi wedge structure consists of two north-northwest–trending fault-bounded panels, each presenting various amounts of fluvial sedimentary and mafic volcanic rocks (Figure GS-1-5a). The western panel is a gently south-dipping, upright, north-northwest–trending synclinal synform with mafic volcanic rocks to the north, and fluvial sedimentary rocks to the south, in the core of the syncline (Figure GS-1-5a). It is the most extensive panel of rocks in the wedge, and extends south to Highway 10. The eastern panel also consists of mafic volcanic and fluvial sedimentary rocks; however, it displays a north-northwest–trending, slightly west-verging anticlinal synform, with fluvial sedimentary rocks unconformably overlying mafic volcanic rocks only to the east (Figure GS-1-5a). These Missi Group rocks can be followed at least 100 m north of the CN Rail line, where they continue to directly overlie the mafic volcanic rocks to the east.

On the regional magnetic survey, the north-northwest Missi wedge structure coincides, especially north of the CN tracks, with a sharp north-northwest–trending break from a high magnetic signature to the west to a low magnetic signature to the east. Stratigraphy extended to the north of this feature and the abrupt north-northwest break in the magnetic survey both suggest that the Missi wedge structure extends well north of the tracks, and therefore crosscuts (and is younger than?) the Railway Faults (Figure GS-1-5a).

Ross Lake Fault

A surface expression of the Ross Lake Fault is not clearly exposed in the area. A potential expression of the fault is a zone of strong shearing just north of Highway 10 on the west side of the Missi wedge. At this locality, fluvial arkosic sedimentary rocks of the Missi Group, to the west, are in sheared contact with mafic volcanic rocks to the east. This zone of shearing extends south through mafic volcanic rocks, between Highway 10 and the water pipeline, and is finally lost in overburden and beneath Ross Lake to the south (Figure GS-1-2). Despite the lack of good exposure of the Ross Lake Fault in the area, its presence is manifest by a clear increase in strain in rocks immediately adjacent to the fault zone and the development of an overprinting ~350–360° foliation.

Mandy Road–Channing area

Stratigraphy

Rocks in the Mandy Road area are the northern extension of those in the Schist Lake–Mandy mines area (Figure GS-1-2; Simard, 2006a, b). The rocks between the Ross Lake and Mandy Road faults are composed mainly of aphyric basaltic flows with lesser amounts of plagioclase-crystal–rich heterolithic mafic breccia. The aphyric basaltic flow sequence is ~300 m thick and consists of 5–10 m thick massive basaltic flows with pillowed and/or amoeboid flow tops. Higher in the stratigraphy, the flows get thinner (2–4 m thick) and eventually only pillowed and amoeboid pillowed flows and amoeboid breccia are left. The plagioclase-crystal–rich heterolithic mafic breccia is massive to crudely bedded, and consists of variably amygdaloidal, subrounded to subangular aphyric basalt clasts (2–25 cm in diameter), with a few (<5%) angular clasts of fine-grained tuffaceous rocks (Figure GS-1-4f). The matrix is variable in composition, but usually has 5–15% plagioclase crystals 2–6 mm in diameter in fine-grained chloritic (mafic tuff?) material.

East of the Mandy Road Fault, rocks are mainly composed of heterolithic mafic breccia with minor aphyric basaltic flows. The heterolithic mafic breccia is massive and consists mainly of variably amygdaloidal, angular to subangular, aphyric basalt clasts (1–70 cm in diameter, averaging 5–7 cm) with a lesser amount of pyroxene-phyric basaltic clasts. The matrix is a fine-grained chloritic (mafic tuff?) material with some pyroxene (~5%) and plagioclase (<3%) crystals. The rocks in this area are intruded by fine- to medium-grained mafic intrusions, locally layered, as well as a late quartz-phyric medium-grained granodiorite.

Rocks in the Channing area are separated from those of the Mandy Road area by the Channing Fault, which offset the quartz-phyric granodiorite (Figures GS-1-2, -5). Not very well exposed, these rocks are composed mainly of massive aphyric basalt with a lesser amount of fine-grained, massive to bedded, mafic volcaniclastic rocks.

All the rocks in the area are unconformably overlain to the north by fluvial sedimentary rocks of the Missi Group (Figures GS-1-2, -4).

Structure

Volcanic rocks between the Ross Lake, Mandy Road, Channing and Cliff Lake faults are among the most deformed in the Flin Flon area (Figures GS-1-2, -5). Although identification of rock types and even volcanic facies is still possible, everything has been considerably flattened in a strong north-trending tectonic fabric, especially on approaching the Ross Lake Fault. This fabric commonly destroys top determination criteria and makes facing directions more challenging to identify than in the Hidden Lake area.

The Ross Lake–Mandy Road fault block is formed from a series of wedge-shaped panels of volcanic rocks, each with a slightly different trend and facing direction (Figure GS-1-5b). The westernmost panel faces west, the middle faces north and the easternmost faces east-northeast (Figure GS-1-5b). These facing direction changes all occur abruptly across narrow shear zones, often hidden in small gullies. The overall rotation of the facing directions is interpreted to be a manifestation of the Mandy Road anticline structure (*see also* Stockwell, 1960), modified by subsequent fault dismemberment (Figures GS-1-2, -5).

Volcanic rocks in the Mandy Road–Channing area always display two distinct foliations: an early, shallowly dipping foliation trending ~015°, overprinted by a late, steeply dipping foliation trending 345–350°. The latter foliation parallels the many narrow sinistral shear zones in the area.

Rocks between the Mandy Road and Channing faults are prominently foliated. They have the same two foliations as rocks in the Ross Lake–Mandy Road fault block but, in addition, contain a late, overprinting, moderately dipping foliation trending 330–335°, adjacent to the Channing Fault. This foliation, which is a product of ductile deformation in the volcanic rocks, is typically a brittle-cataclastic fabric in the quartz-phyric granodiorite, which is crosscut by the Channing Fault.

Rocks in the Channing area between the Channing and Cliff Lake faults display only the two foliations: the earlier, steeply dipping foliation trending 345–350° and the late, moderately dipping foliation trending 330–335°.

Geochemistry

Analytical techniques, alteration and sampling

Fifty representative rock samples were selected for geochemical analysis from a suite of over 150 specimens collected during the mapping of the Schist Lake–Mandy mines area. Major and trace-element compositions of all the analyzed samples are available in Data Repository Item DRI2007001[1].

All samples were analyzed at Activation Laboratories Ltd., Ancaster, Ontario, with major-element concentrations determined by x-ray fluorescence (XRF), trace elements and rare earth elements (REE) by inductively coupled plasma–mass spectrometry (ICP-MS; using fusion for sample preparation), and Sc by instrumental neutron activation analysis (INAA). Analytical error for the XRF method was <1% for major elements. For trace elements, precision is better than 6% and analytical error is better than 5% (Young, 2002). Eight samples were analyzed for Sm and Nd concentrations and Nd isotopic compositions at the Radiogenic Isotope Facility, University of Alberta, Edmonton, Alberta (Table GS-1-1).

Although primary minerals were replaced by lower-greenschist–facies metamorphic mineral assemblages, most major elements, high field-strength elements (HFSE), REE, Th and transition elements are considered to have been immobile during this lower-greenschist–facies metamorphism (e.g., Pearce and Cann, 1973; Winchester and Floyd, 1977; Wood, 1980; MacLean, 1990; Jenner, 1996). The consistency in compositional trends using both mobile and immobile elements in these volcanic rocks, and their similarities to those of modern igneous rocks, support the authors' interpretation that most major and trace elements were not significantly

[1] MGS Data Repository Item DRI 2007001, containing the data or other information sources used to compile this report, is available online to download free of charge at http://www2.gov.mb.ca/itm-cat/freedownloads.htm, or on request from minesinfo@gov.mb.ca. or Mineral Resources Library, Manitoba Science, Technology, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada.

Table GS-1-1: Neodymium and samarium isotopic analyses of volcanic rocks from of the Schist Lake–Mandy mines area.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	uncert.	TDM	~T(ma)	εNd(T)
105-06-19-4-3	3.21	11.96	0.1622	0.51236	0.00001	N/A	1900	2.9
105-06-31-1-1	3.74	14.41	0.1568	0.51230	0.00001	N/A	1900	3.1
105-06-92-2-1	1.20	3.84	0.1886	0.51263	0.00001	N/A	1900	1.8
105-06-96-2-2	1.48	6.01	0.1492	0.51210	0.00001	N/A	1900	1.1
105-06-111-2-1	4.27	16.71	0.1544	0.51228	0.00001	N/A	1900	3.4
105-06-139-1-1	2.64	10.33	0.1547	0.51223	0.00001	N/A	1900	2.4
105-06-157-1-1	1.85	6.22	0.1794	0.51254	0.00001	N/A	1900	2.3
105-06-164-1-1	1.46	5.50	0.1610	0.51237	0.00002	N/A	1900	3.4

affected by alteration or metamorphic processes. Thus, their distribution likely reflects primary magmatic trends.

Schist Lake–Mandy mines area

Rocks of the Schist Lake–Mandy mines area are divided into four different packages based on the observed stratigraphy: 1) the Hidden formation, 2) the Louis formation, 3) west of the Burley Lake Fault, and 4) east of the Mandy Road Fault (Simard, 2006a, b; Figure GS-1-2). Because many of them display major overlap in geochemical signatures, they are described together where applicable.

Mafic volcanic rocks

Most mafic flows in the Schist Lake–Mandy mines area are basalt to basaltic andesite with low Zr/TiO_2 (0.020–0.142) values (Figure GS-1-6a). The low Nb/Y (0.04–0.15) values suggest subalkaline affinity (Figure GS-1-6a).

The REE patterns of the mafic flows of the Hidden formation (Figure GS-1-7b) show a small light REE (LREE) enrichment ($(La/Yb)_N$ = 0.91–2.13) with a flat heavy REE (HREE) pattern. The REE patterns of the mafic flows of the Louis formation, as well as the basalt flows west of the Burley Fault and some of the basalt flows east of the Mandy Road Fault (Figure GS-1-7b, c), show a small to moderate LREE enrichment ($(La/Yb)_N$ = 1.30–4.53) with a flat HREE pattern. The flat HREE pattern suggests that the source areas(s) of these mafic magma(s) did not contain any garnet; therefore, they were probably produced from partial melting in the spinel peridotite field at <60 km depth (White et al., 1992).

The pronounced negative Nb and Ti anomalies on mantle-normalized trace-element diagrams (Figure GS-1-7b, c), low Ti/V ratios (Figure GS-1-6b) and distribution on the Th–(Zr/117)–Nb/16 (Figure GS-1-6c; Wood, 1980) and Zr/3–(Nb×2)–Y (Figure GS-1-6d; Meschede, 1986) diagrams all indicate mafic flows in the Schist Lake–Mandy mines area to be products of subduction-related processes in an oceanic arc environment. Their relatively low $(La/Yb)_N$ ratios and high FeO_{total}/MgO ratios clearly demonstrate a tholeiitic affinity.

Analyses of Sm-Nd isotopes from the mafic volcanic rocks of the Schist Lake–Mandy mines area display an overall range of $\varepsilon_{Nd(1900Ma)}$ values from +1.1 to +3.4 (Table GS-1-1). Hidden formation mafic flows show $\varepsilon_{Nd(1900Ma)}$ values from +1.8 to +3.4, whereas the mafic flows from west of the Burley Lake Fault and east of the Mandy Road Fault show $\varepsilon_{Nd(1903Ma)}$ values of +2.4 and +2.3, respectively. No mafic flows of the Louis formation were submitted from the Schist Lake–Mandy mines area, as several $\varepsilon_{Nd(1900Ma)}$ values have already been published for these rocks ($\varepsilon_{Nd(1900Ma)}$= +3.3 to +3.9; Stern et al., 1995a). The positive $\varepsilon_{Nd(1900Ma)}$ values of these rocks suggest a juvenile magma source with minimum involvement of continental crust in the magma genesis; however, the slightly less positive $\varepsilon_{Nd(1900Ma)}$ values for the Hidden formation rocks compared to the Louis formation rocks suggest potentially more contamination of the Hidden formation rocks.

Felsic volcanic rocks

Felsic volcanic rocks in the Schist Lake–Mandy mines area consist of isolated, small, massive to locally brecciated, plagioclase-quartz–phyric rhyolite flows/domes in both the Hidden and Louis formation rocks. The Hidden formation rhyolitic rocks are spatially associated with numerous, narrow, aphyric to quartz-plagioclase–phyric rhyolitic dikes, which cut Hidden formation rocks and are likely feeders to the flow/domes. The analyzed samples have high SiO_2 content (SiO_2 >72.7%) with low Nb/Y (0.07–0.08) and high Zr/TiO_2 (0.362–0.427) values (Figure GS-1-6a). The low Nb/Y values suggest subalkaline affinity (Figure GS-1-6a). The content of HFSE (Nb, Ta, Ga, Zr, Hf and Y), relative to other incompatible elements within these rocks, is moderate to low and characteristic of rocks generated in an oceanic arc environment (Figure GS-1-6c, -6d; Wood, 1980; Meschede, 1986).

The REE patterns of the felsic flows of the Hidden and Louis formations (Figure GS-1-7b) show slight LREE enrichment ($(La/Yb)_N$ = 1.76–2.23) with a relatively flat HREE pattern. These REE patterns are very similar to those of the mafic flows from the Hidden and

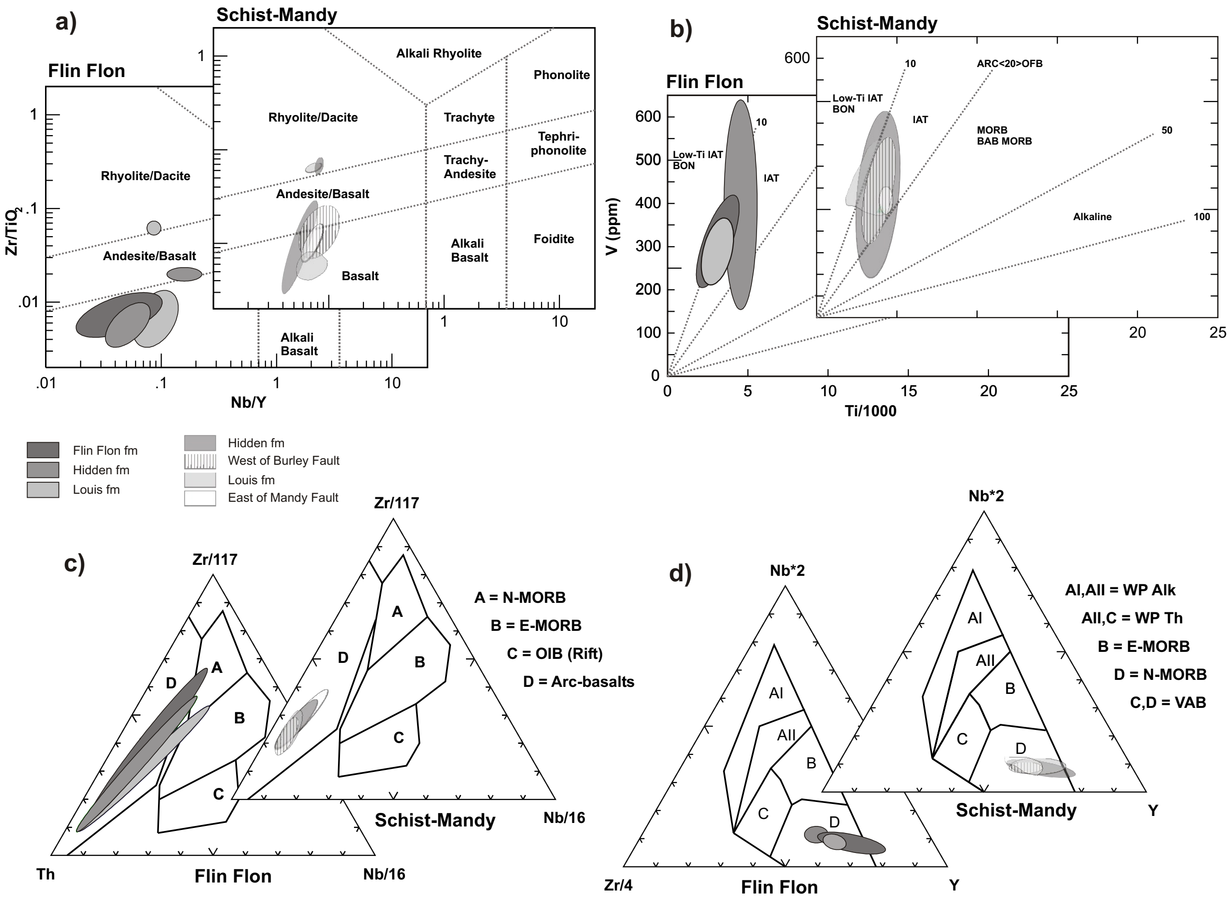

***Figure GS-1-6:** Geochemical characteristics of the volcanic rocks in the Schist Lake–Mandy mines area; **a)** Zr/TiO_2 vs. Nb/Y classification diagram (*modified from *Winchester and Floyd, 1976); **b)** V–(Ti/1000) diagram of Shervais (1982), with V/Ti <20 typical of arc and V/Ti >50 typical of alkali magmatism. Abbreviations: BAB, back-arc basalt; BON, boninite; IAT, island-arc tholeiite; MORB, mid-ocean-ridge basalt; OFB, ocean floor basalt; **c)** Th–(Zr/117)–(Mb/16) diagram *from* Wood (1980). Abbreviations: E-MORB, enriched-MORB; N-MORB, normal-MORB; OIB, ocean-island basalt; **d)** (Zr/4)/(Nb×2)/Y diagram of Meschede (1986). Abbreviations: alk, alkali; Th, tholeiite; VAB, volcanic arc basalt; WP, within-plate.*

Louis formations, suggesting that they are derived from the same source. Similar to the mafic flows in this area, felsic flows of the Schist Lake–Mandy mines area display pronounced negative Nb and Ti anomalies on the mantle-normalized trace-element diagrams (Figure GS-1-7b). This, plus their Ti/V ratio (Figure GS-1-6b) and their distribution on the Th–(Zr/117)–Nb/16 (Figure GS-1-6c; Wood, 1980) and Zr/3–(Nb×2)–Y (Figure GS-1-6d; Meschede, 1986) diagrams suggest subduction-related genesis in an oceanic arc environment.

Analyses of Sm-Nd isotopes of the felsic volcanic rocks from the Hidden formation show $\varepsilon_{Nd(1900Ma)}$ values of +3.1, whereas those from the Louis formation show $\varepsilon_{Nd(1903Ma)}$ values of +3.4 (Table GS-1-1). The positive $\varepsilon_{Nd(1900Ma)}$ values of these rocks, which are similar to mafic flows in the area, suggest a juvenile magma source with little involvement of continental crust in magma genesis.

Discussion and economic considerations

Flin Flon area stratigraphy

Extrapolating the Flin Flon–Callinan–Triple 7 mine stratigraphy, based on volcanic stratigraphy or geochemistry, beyond the immediate Flin Flon mine area has proven difficult. Proximal volcanic arc environments, such as those in which Flin Flon rocks were formed, display highly variable stratigraphy due to multiple volcanic centres, local subsidence structures and the sporadic nature of volcanic activity. These features make confident extrapolation of stratigraphy between two areas difficult, even when these areas are as close to one another as the Hidden Lake and Schist Lake–Mandy mines areas (5 km separation).

Rocks between the Ross Lake and Mandy Road faults, in the Schist Lake–Mandy mines area (Figure GS-1-2), are mainly thick aphyric basaltic flows with lesser amounts of plagioclase-crystal–rich heterolithic mafic breccia, and are most similar to those in the Hidden formation north of Flin Flon. Although a greater abundance of heterolithic mafic breccia and local enrichment in plagioclase crystals is somewhat compatible with the rocks belonging to the Blue Lagoon member of the Flin Flon formation (Figure GS-1-3), the presence of comformably overlying rocks of the Louis formation west

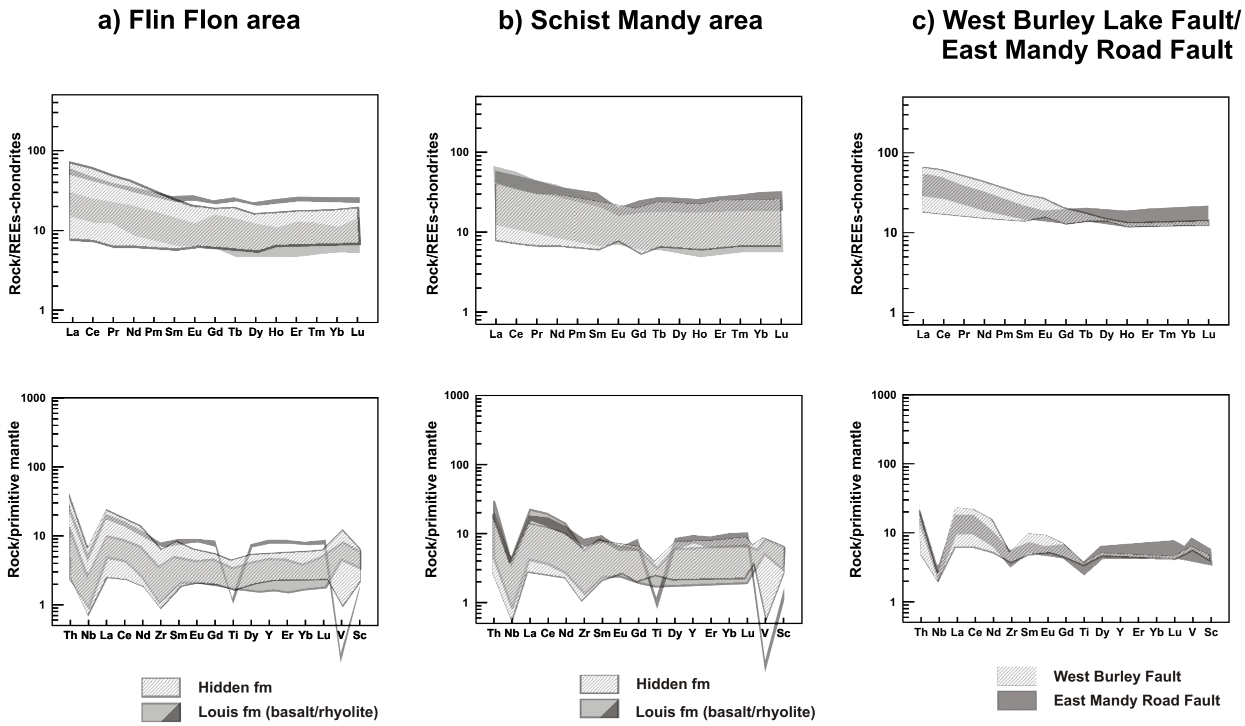

Figure GS-1-7: *Chondrite-normalized rare-earth-element patterns (normalization values* from *McDonough and Sun, 1995) and mantle-normalized incompatible trace-element patterns (normalization values* from *Sun and McDonough, 1989) for the volcanic rocks of* ***a)*** *the Hidden and Louis formations of the Flin Flon area,* ***b)*** *the Hidden and Louis formations of the Schist Lake–Mandy mines area, and* ***c)*** *west Burley Lake Fault and east Mandy Road Fault.*

of the Ross Lake Fault (Figure GS-1-2) is more consistent with the rocks belonging to the Hidden formation.

Rocks east of the Mandy Road Fault are heterolithic mafic breccia (not plagioclase-crystal rich) with minor aphyric basaltic flows, and are the hostrocks of the Schist Lake and Mandy VMS deposits to the south (Figure GS-1-2). If the Mandy Road Fault was not present, these rocks would be sitting just below the Hidden formation rocks to the west and be correlative with the hangingwall rocks of the Flin Flon–Callinan–Triple 7 VMS deposits. This has made a potential correlation with the main Flin Flon VMS stratigraphy enticing. In the Flin Flon main camp, however, the VMS-bearing Flin Flon formation does not have the abundant non-plagioclase–phyric heterolithic breccia that is seen east of the Mandy Road Fault. This suggests that the rocks east of the Mandy Road Fault, which include the rocks of the Schist Lake and Mandy mines, are not likely to be part of the Flin Flon–Callinan–Triple 7 mine stratigraphy.

Flin Flon area geochemistry

Although volcanic rock geochemistry is a powerful tool to characterize volcanic packages, it has limitations. This is particularly true when applied to very small areas where the differences between similar volcanic packages are small. Rocks of the Flin Flon–Callinan–Triple 7 mine stratigraphy display very similar whole-rock and isotopic geochemical signatures with only subtle variations, if any, between the footwall and hangingwall packages (Figures GS-1-6, -7; DeWolfe, pers. comm., 2007; Gibson, unpublished data, 2000–2007). The Flin Flon–Callinan–Triple 7 footwall and hangingwall volcanic rocks are both the result of tholeiitic arc volcanism (Syme et al., 1999) with relatively juvenile isotopic signatures (i.e., positive ε_{Nd} values of +2 to +5; Stern et al., 1995a, b). Thus, it is virtually impossible to differentiate rocks of the Flin Flon formation (footwall sequence) from those of the Hidden formation (hangingwall sequence) solely using geochemistry (Figures GS-1-6, -7). Within the hangingwall stratigraphy, small geochemical differences do exist between rocks of the Hidden and Louis formations, but there is also considerable overlap in their geochemical signatures that, once again, prevents differentiating these two formation based solely on geochemistry.

If the rocks of the Schist Lake–Mandy mines area are compared to those of the Flin Flon–Callinan–Triple 7 mine stratigraphy, they clearly show geochemical similarities (Figures GS-1-6, -7). The aphyric basaltic flows west of the Mandy Road Fault show the same geochemical characteristics as the typical Hidden formation aphyric basaltic flows of the Flin Flon mines area, with low Nb/Y and Zr/TiO_2 ratios as well as small LREE enrichment with a relatively flat HREE pattern on the REE and mantle-normalized trace-element diagrams (Figures GS-1-6, -7; DeWolfe, pers. comm., 2007). Farther west, the pyroxene-plagioclase–phyric basaltic flows on the peninsula in Phantom Lake show geochemical characteristics similar to the typical Louis formation pyroxene-plagioclase–phyric basaltic flows of the Flin Flon mines area, with low Nb/Y and Zr/TiO_2 ratios as well as moderate LREE enrichment and a flat HREE pattern on the REE and mantle-normalized trace-element diagrams (Figures GS-1-6, -7; DeWolfe, pers. comm., 2007). All the analyzed felsic volcanic rocks in the area, the Hidden and Louis formation flows/lobes and dikes alike, display a very similar geochemical signature when compared to the Flin Flon mine rhyolite.

The aphyric to pyroxene-plagioclase–phyric basaltic volcanic rocks west of the Burley Lake Fault share similarities with the Louis formation basalt, in particular their moderate LREE enrichment on the REE diagram. The scarcity of analyses for rocks east of the Mandy Road Fault, combined with their considerable variability, currently prevents any conclusive comparison to the Flin Flon–Callinan–Triple 7 mine package based on geochemistry.

Analyses of Sm-Nd isotopes from mafic and felsic volcanic rocks of the Schist Lake–Mandy mines area display an overall range of $\varepsilon_{Nd(1900Ma)}$ values (+1.8 to +3.4; Table GS-1-1) that is slightly lower than those published in the past for the volcanic rocks of the Flin Flon–Callinan–Triple 7 mine stratigraphy (+3.1 to +4.7; Stern et al., 1995b; DeWolfe, pers. comm., 2007). The slightly less positive $\varepsilon_{Nd(1900Ma)}$ values of these rocks suggest that their magma source may have undergone greater contamination by sedimentary rocks or older continental crust than previously documented for the rocks of the Flin Flon area.

Future work

Detailed mapping of both the structures and the volcanic facies, and thorough geochemical characterization of the volcanic rocks in the Flin Flon area have proven crucial to documenting and establishing the Flin Flon–Callinan–Triple 7 mine stratigraphy and more accurately assessing its extent in the area. It has enabled the ongoing production of a new 1:10 000 scale stratigraphic cross-border map for the Flin Flon area, and this will be crucial to the formulation of successful exploration models for this area.

More work is still required, and is in part currently underway (Lewis et al., in press; Lafrance, unpublished work, 2005–2007), to better understand the structural evolution of the immediate Flin Flon area. This is needed to better evaluate the timing and effects of the multiple deformation events (thrust faults, folds, strike-slip faults) on the distribution of the mine stratigraphy. Although individual structures, such as the Hidden Lake syncline, the Railway Faults, the Missi wedge structure and the Ross Lake Fault, are readily documented, their relative timing is still not adequately resolved.

More investigations (Cole et al., GS-3, this volume; Gibson, unpublished work, 2006–2007) are underway with the objective of resolving problems of correlation between the VMS-hosting units at the Schist Lake and Mandy mines (east of Mandy Road Fault) and those that host the Flin Flon, Callinan and Triple 7 orebodies.

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