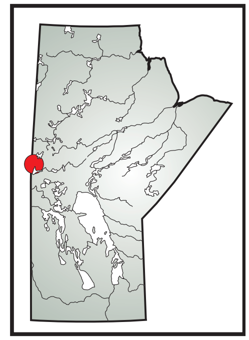
# GS-3 Stratigraphy and structural geology of the structural hangingwall to the hostrocks of the Schist Lake and Mandy volcanogenic massive sulphide deposits, Flin Flon, Manitoba (part of NTS 63K12)

by Y. M. DeWolfe[1]



DeWolfe, Y.M. 2009: Stratigraphy and structural geology of the hangingwall to the hostrocks of the Schist Lake and Mandy volcanogenic massive sulphide deposits, Flin Flon, Manitoba (part of NTS 63K12); *in* Report of Activities 2009, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 22–36.

## Summary

The Paleoproterozoic Glennie–Flin Flon Complex is part of the southeastern Reindeer Zone of the Trans-Hudson Orogen and contains 27 known volcanogenic massive sulphide (VMS) deposits. Two of these, the Schist Lake and Mandy deposits, are located on the western edge of the Northwest Arm of Schist Lake in northwestern Manitoba, approximately 4 km southeast of the town of Flin Flon, and are currently inactive.

Detailed mapping (1:2000 scale) of the strata that structurally overlie the hostrocks of the Schist Lake and Mandy deposits was the focus of fieldwork during the summer of 2009. The study area is located within the Flin Flon arc assemblage, in the Hidden formation, and is bounded to the west by a north-trending fault separating the Hidden formation from the Louis formation, and to the east by the north-oriented Cliff Lake Fault. From the west shoreline of the Northwest Arm of Schist Lake to Carlisle Lake there is a sequence of dominantly mafic volcaniclastic rocks, with lesser basaltic flows. This sequence could be equivalent to the hangingwall stratigraphy for the Schist Lake and Mandy deposits, with younging directions consistently to the west, depending on the displacement on the Mandy Road faults.

Bedrock mapping of the area containing the Mandy Road anticline, located approximately 1 km north of the Schist Lake–Carlisle Lake section, revealed bedding orientations that change in strike from 340° (dipping and younging east on the east limb of the fold) to 308° (dipping and younging north at the nose of the fold) to 010° (dipping and younging east on what has been previously interpreted as the west limb of the anticline). A preliminary interpretation for this change in bedding orientation is that a north-south sinistral fault crosscuts the anticline and has rotated the west limb clockwise into its current orientation.

## Introduction

The volcanic rocks near the town of Flin Flon host current (Callinan, 777 and Trout Lake) and past-producing (Flin Flon, Schist Lake and Mandy) VMS deposits (Figures GS-3-1, -2). Collectively, these deposits total more than 90 million tonnes and constitute one of the largest massive sulphide districts in the Proterozoic (Bailes and Syme, 1989; Syme et al., 1999; Devine et al., 2002; Devine, 2003; Gibson et al., 2003).

Rocks that host the Schist Lake and Mandy deposits are part of an undivided package of volcanic rocks that lies just east of the Flin Flon Block across the Mandy Road faults. This project concentrates on mapping the volcanic rocks of the Hidden formation, just west of the Mandy Road faults, and the rocks that host the Schist Lake and Mandy deposits, just east of the Mandy Road faults, with the goal of reconstructing the volcanic environment of the deposits to aid exploration in the area and in similar terranes worldwide. The mapping for this project will take place over two field seasons, the first of which was completed in the summer of 2009. This report summarizes the results of a five-week bedrock mapping and sampling program that took place during the summer of 2009 in the Schist Lake–Mandy mines area. Mapping focused on the Hidden formation strata west of the Mandy Road faults, and in the Mandy Road anticline area (Schist Lake–Carlisle Lake section and Mandy Road anticline area; Figure GS-3-3). Mapping during the summer of 2010 will concentrate on the strata east of the Mandy Road faults, which host the Schist Lake and Mandy deposits, as well as areas west of the Mandy Road faults that were not mapped during the 2009 field season (Figure GS-3-3).

## Objectives and methodology

This study focuses on the strata that structurally overlie the rocks hosting the Schist Lake and Mandy deposits, in the Schist Lake, Mandy Lake and Mandy Road anticline area, and builds on the work of Simard (2006) and Cole et al. (2007, 2008). Mapping at 1:2000 scale forms the basis of this research and will be augmented with petrography, trace and rare earth element analysis and geochronology.

Specific objectives of this two-year project are to

- establish a detailed litho- and chemostratigraphy for the rocks that host the Schist Lake and Mandy deposits, and the structurally overlying sequence of Hidden formation west of the Mandy Road faults;

[1] Department of Earth Sciences, Mount Royal University, 4825 Mount Royal Gate, Calgary, Alberta T3E 6K6

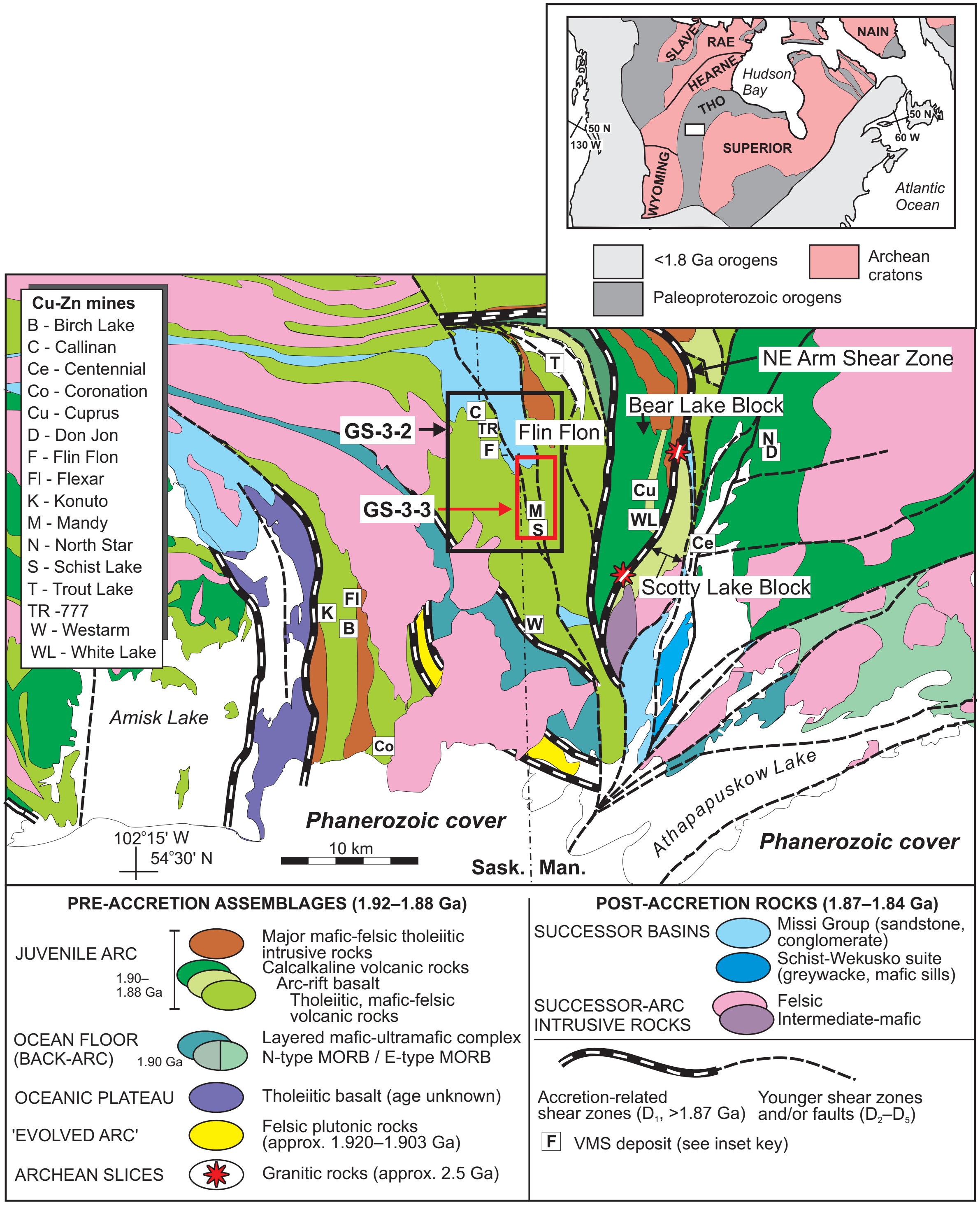



***Figure GS-3-1:** Geology of the Glennie–Flin Flon Complex, showing the locations of known volcanogenic massive sulphide (VMS) deposits (*modified from *Syme et al., 1999*); box indicates the area covered by Figure GS-3-2; inset map shows the location of the Glennie–Flin Flon Complex within the Trans-Hudson Orogen (THO).*

- determine if the Mandy Road faults have significantly affected the strata in the Schist Lake–Mandy mines area (i.e., have the faults structurally juxtaposed two different strata?);
- determine if previous interpretations of the Mandy Road anticline and its morphology are correct, and determine the exact location of its fold axis;
- reconstruct the volcanic environment and emplacement/depositional history of these strata, including the location of synvolcanic faults (building on the observations of Simard, 2006);
- determine if synvolcanic structures recognized in these rocks can be traced downwards and across the Mandy Road faults into the host strata of the Schist

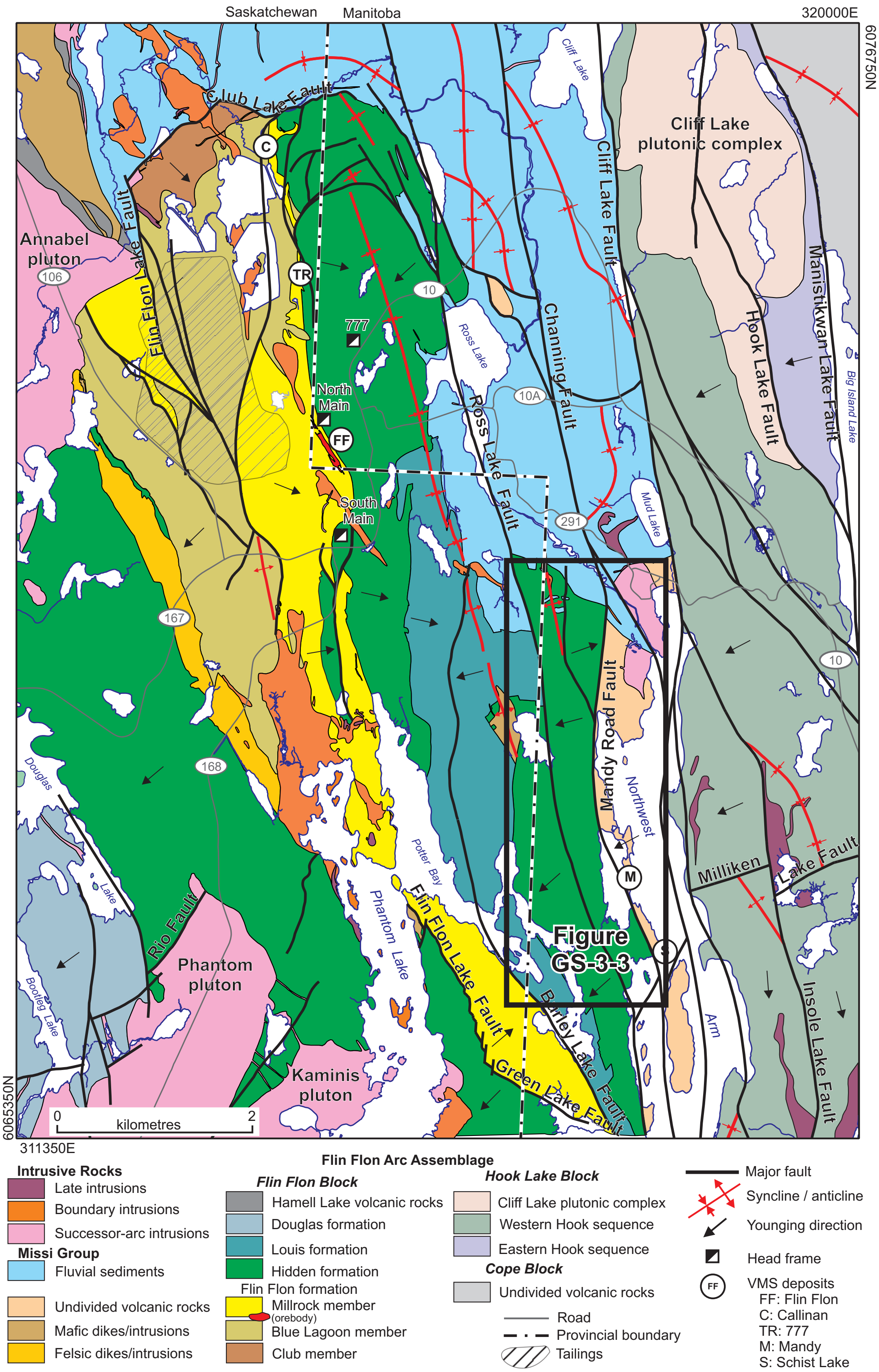



***Figure GS-3-2:*** *Simplified geology of the Flin Flon area, showing the major stratigraphic units and structures (*modified from *Simard and McGregor, GS-2, this volume); box indicates the area covered by Figure GS-3-3.*

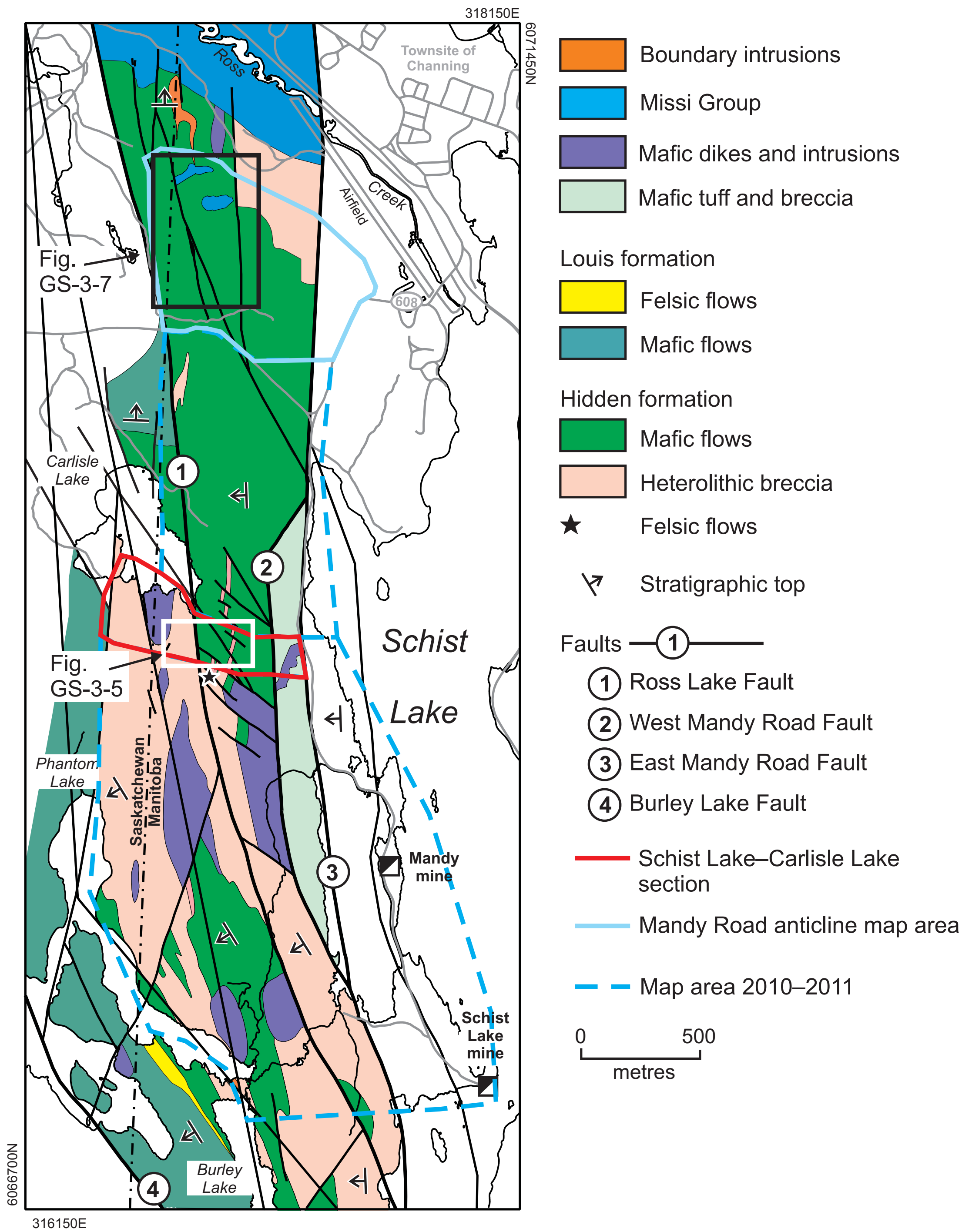



***Figure GS-3-3:** Simplified bedrock geology of the Schist Lake–Mandy mines area, Flin Flon, Manitoba* (modified from *Simard, 2006).*

and Mandy deposits, and if so, do they correspond with the location of VMS mineralization;

- document, delimit and describe the hydrothermal alteration assemblages within the strata (building on the work of Cole et al., 2008); and
- assess the potential for undiscovered base-metal mineralization within these rocks, specifically with respect to the Schist Lake and Mandy deposits.

## Regional geology

The Paleoproterozoic Glennie–Flin Flon Complex is part of the southeastern Reindeer Zone of the Trans-Hudson Orogen and contains 27 known VMS deposits (Figure GS-3-1). The complex consists of a series of 1.91–1.84 Ga juvenile-arc, back-arc, ocean-floor and evolved-plutonic-arc tectonostratigraphic assemblages (Bailes and Syme, 1989; Stern et al., 1995; Lucas et al., 1996; Lucas et al., 1997; Bailes and Galley, 1999; Stern et al., 1999). The Flin Flon and Snow Lake juvenile-arc assemblages contain the majority of the VMS deposits (Syme et al., 1999).

The study area is located within the rocks of the Flin Flon arc assemblage, 2 km southeast of the town of Flin Flon (Figure GS-3-2**)**. The Flin Flon arc assemblage is composed of juvenile metavolcanic rocks (1.91–1.88 Ga) that are unconformably overlain by younger fluvial sedimentary rocks of the Missi Group (ca. 1.84 Ga; Bailes and Syme, 1989; Stern et al., 1995; Lucas et al., 1996). Rocks of the Flin Flon arc assemblage are interpreted to have been erupted and emplaced in an island-arc–back-arc setting, and consist of basalt, basaltic andesite flows and breccia with lesser rhyolitic flows (Syme and Bailes, 1993). The Flin Flon, Callinan and 777 VMS deposits, which total more than 86 million tonnes grading 2.2% Cu, 4.3% Zn, 2.49 g/t Au and 38.16 g/t Ag, are interpreted to have formed during a period of localized rhyolitic volcanism in a synvolcanic subsidence structure, or cauldron, within a much larger, dominantly basaltic, central volcanic complex (Figure GS-3-2; Bailes and Syme, 1989; Syme et al., 1999; Devine et al., 2002; Devine, 2003). The Schist Lake (1.8 million tonnes of 4.3% Cu, 7.27% Zn, 1.3 g/t Au and 37 g/t Ag) and Mandy (0.13 million tonnes of 7.3% Cu, 12.9% Zn, 2.8 g/t Au, 57 g/t Ag) VMS deposits are hosted by a quartz porphyritic rhyolite unit that is compositionally similar to that which hosts the Flin Flon, Callinan and 777 VMS deposits. These deposits are structurally overlain, across the Mandy Road faults, by basaltic–andesitic flows, sills and volcaniclastic rocks that are similar to the rocks overlying the main Flin Flon VMS deposits (Figure GS-3-3; Simard, 2006).

## Geology of the Hidden formation strata structurally overlying the hostrocks to the Schist Lake and Mandy VMS deposits

Volcanic rocks that structurally overlie the hostrocks to the Schist Lake and Mandy VMS deposits, and could potentially constitute the hangingwall strata, have been correlated with the volcanic rocks of the Hidden and Louis formations (Bailes and Syme, 1989; Simard, 2006; Simard and Creaser, 2007). The Hidden and Louis formations form the lower and upper units, respectively, within the hangingwall to the Flin Flon, Callinan and 777 VMS deposits (DeWolfe et al., 2009). In the Schist Lake–Mandy mines area, strata of the Hidden formation occur west of the Mandy Road faults, where they trend north, dip steeply to the east and young to the west (Figure GS-3-3). To the north, they are in unconformable contact with the younger sedimentary rocks of the Missi Group.

In the study area, rocks of the Hidden formation consist of aphyric to weakly plagioclase-phyric basalt flows, intercalated with mafic and heterolithic volcaniclastic rocks. Basaltic flows are the dominant lithofacies in the northern part of the area, whereas volcaniclastic rocks are the dominant lithofacies to the south (Simard, 2006). Lithofacies descriptions for the Schist Lake–Carlisle Lake section and the Mandy Road anticline map area (Figure GS-3-3**)** are described below, separately and in stratigraphic order from oldest to youngest.

In these descriptions, a nongenetic terminology for volcaniclastic rocks is used because distinguishing primary and resedimented volcaniclastic deposits in the field is difficult. The deposits are described using the nongenetic, granulometric names tuff, lapilli tuff, lapillistone, and tuff breccia that only reflect the percentage and size of the components (Fisher, 1961; Gibson et al., 1999; White and Houghton, 2006). In this terminology, tuff contains particles <2 mm, lapilli are 2–64 mm, and blocks and bombs are particles >64 mm. Peperite is "a genetic term applied to a rock formed essentially in situ by disintegration of magma intruding and mingling with poorly consolidated, typically wet sediments" (White et al., 2000).

### *Schist Lake–Carlisle Lake section*

The base of the stratigraphic section is located west of the Mandy road and continues to the faulted contact between the Hidden and Louis formations just west of Carlisle Lake (Figure GS-3-3). Detailed descriptions of mafic volcaniclastic rocks east of the Mandy road are contained in Cole et al. (2007). Both rock packages are separated by the East Mandy Fault, which runs 'under' the Mandy road (Figure GS-3-3).

As mentioned previously, the volcanic lithofacies are highly variable along strike in this area (Simard, 2006; Simard and Creaser, 2007). The Schist Lake–Carlisle Lake section is located just south of the transition from mainly basaltic-flow lithofacies in the north to mainly volcaniclastic lithofacies in the south (Figure GS-3-3**)**. Figure GS-3-4 shows a schematic stratigraphic column for the Schist Lake–Carlisle Lake section. Figure GS-3-5 shows the detailed geology of the main portion of the Schist Lake–Carlisle Lake section, just east of Carlisle Lake, that was used to build part of this stratigraphic column.

#### Mafic tuff

A 200 m thick (approximately) unit of mafic tuff occurs at the base of the section. The tuff has been traced along strike for approximately 200 m to the north and more than 1 km to the south, west of the East Mandy Road Fault (Simard, 2006).

The unit consists of interbedded, finely laminated mafic tuff beds (10–60 cm), massive mafic tuff beds (30–100 cm) and plagioclase crystal–rich tuff beds (10–100 cm). Nonmassive beds within this unit are commonly parallel laminated and seldom crosslaminated (Figure GS-3-6a). The plagioclase crystal–rich beds are massive and contain 10–50%, subrounded to rounded plagioclase crystals that are 1–5 mm in size. Massive beds commonly

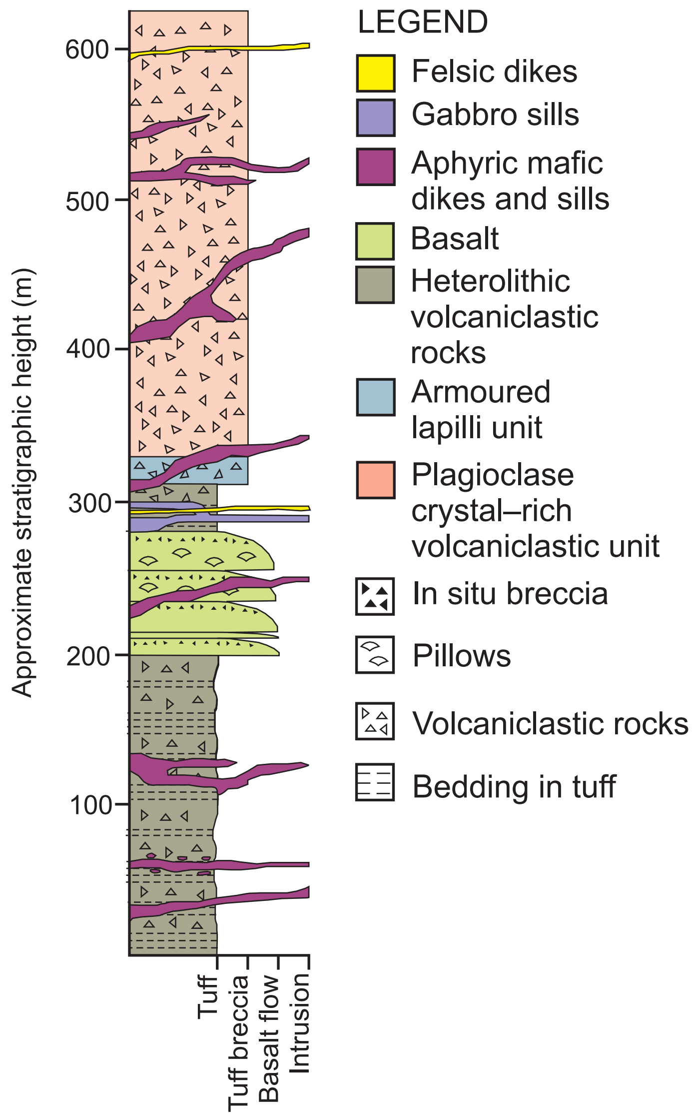



***Figure GS-3-4:*** *Schematic stratigraphic column for the Schist Lake–Carlisle Lake section.*

show normal grading, and both grading and crosslaminations suggest that the unit youngs to the west. Locally, the mafic tuff beds are tightly folded, showing S- and Z-folds that plunge gently to the south.

Numerous sills and dikes occur within this unit, forming up to 30% of some outcrops. Peperite occurs at the contacts of some the sills and dikes. The lower contact of the mafic tuff with the underlying mafic volcaniclastic units and the upper contact with the overlying basalt flows are not exposed in this area. Previous work suggests that these contacts are structural (West and East Mandy Road faults, Figure GS-3-3; Bailes and Syme, 1989; Simard et al., 2009). Further work is required to address this issue.

### Basaltic flows

Massive basalt occurs stratigraphically above the mafic tuff unit. This basalt is approximately 60 m thick (not true thickness) and is divisible into three separate flows (Figures GS-3-4, -5): a lowermost flow that is approximately 20 m thick with a 1 m thick flow-top breccia, a 5 m thick flow with a 1 m thick flow-top breccia, and an uppermost 35 m thick flow with a 1–8 m thick flow-top breccia. Overlying the massive basalt flows are two pillowed basaltic flows. The lower pillowed flow is approximately 40 m thick with a 1–3 m thick flow-top breccia; the upper pillowed flow is approximately 60 m thick and is conformably overlain by the overlying mafic volcaniclastic rocks (Figures GS-3-4, -5).

Massive basalt is brownish green, aphyric and amygdaloidal (5–40%, 1–4 mm, quartz filled), with amygdules increasing in abundance towards the tops of individual flows. The flow-top breccias are clast supported and characterized by amoeboid clasts (2–20 cm) of brownish green aphyric basalt with thin (1–2 mm) chilled margins, in a fine-grained, reddish brown matrix. Quartz-epidote alteration occurs throughout the unit and manifests itself as light greenish brown patches, 10–100 cm in length,

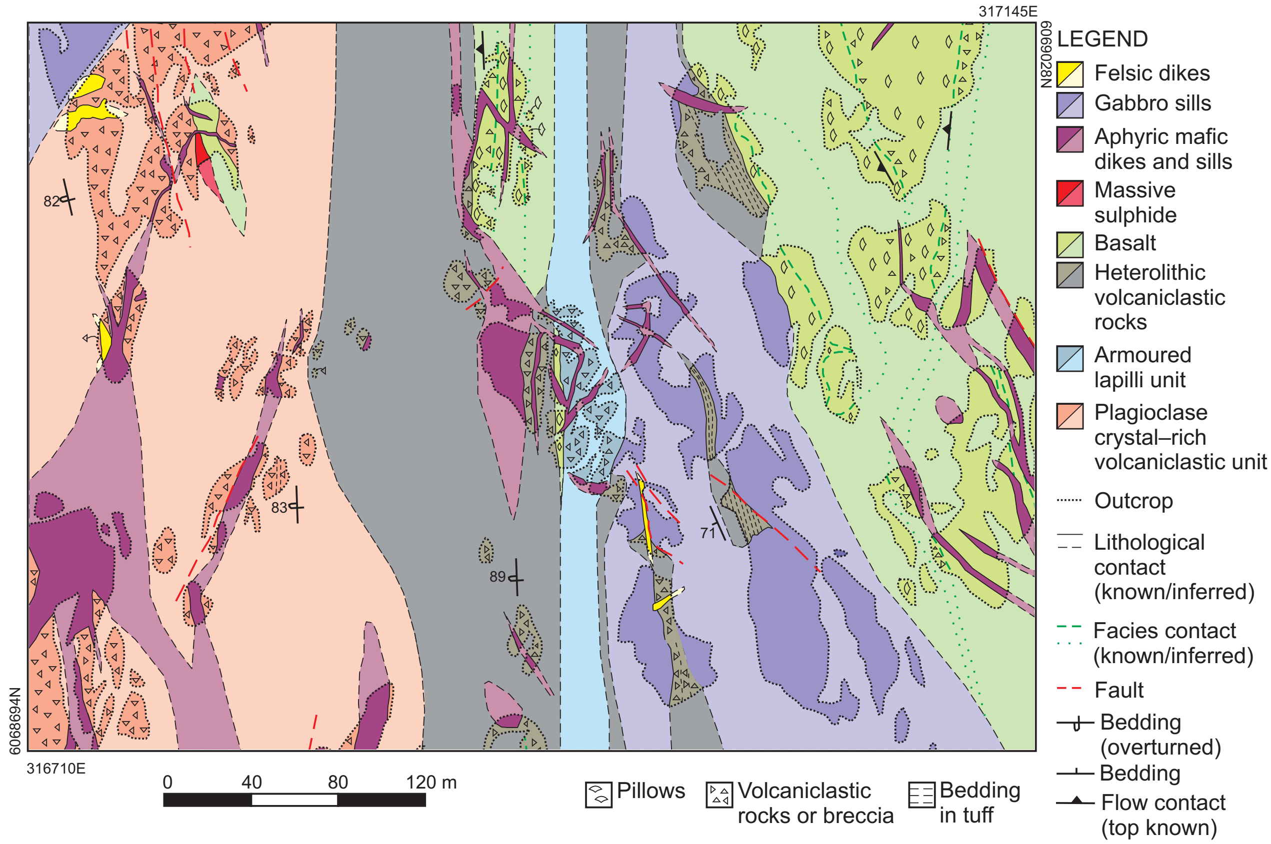



***Figure GS-3-5:*** *Detailed geology of the Hidden formation southeast of Carlisle Lake.*

that have a preferential orientation of 340°. Quartz-epidote alteration ranges from weak to strong, and is most intense in the thin, 5 m thick flow and at the base of the upper 35 m thick flow.

The pillowed flows are aphyric to weakly plagioclase phyric (<5%), brown and amygdaloidal (5–40%, 1–50 mm, quartz filled; Figure GS-3-6b). The pillows range in size from 0.5 to 4 m, with some larger megapillows present (4–10 m in diameter). The selvages are 1–10 cm wide and are strongly quartz-epidote altered; moderate quartz-epidote alteration occurs throughout the pillows. The lower flow has a well-defined flow-top breccia (Figure GS-3-6c) containing amoeboid clasts (1–45 cm) of basalt, with fine-grained chilled margins, in a reddish brown, fine-grained matrix containing approximately 5% plagioclase crystals (1 mm, angular to subangular); lobes within the breccia are locally imbricated. The pillows of the upper flow commonly display concentric thermal-contraction cracks.

The lower contact of the massive basalt flows with the underlying mafic tuff is not exposed, whereas the upper contact is defined by a flow-top breccia. The upper pillowed flow is in sharp but irregular contact with an overlying plagioclase crystal–rich tuff unit.

**Mafic volcaniclastic unit**

This unit occurs stratigraphically above the pillowed basalts and is approximately 200 m thick, but thickness estimates are complicated by a gabbroic sill (Figures GS-3-4, -5) located along its lower contact. A distinctive, 25 m thick unit containing lapilli and blocks rimmed by fine-grained basalt occurs within the volcaniclastic unit. This unit is described in the next section.

The base of the unit is a thick (15 m) tuff composed of intercalated finely laminated and massive beds. The tuff is dominated by very fine grained mafic tuff beds with minor (≤10%) coarser tuff beds. There are also minor (≤10%) felsic tuff beds (≤20 cm each). The mafic tuff beds are ≤40 cm thick and are commonly normally graded, with coarser bottoms and finer tops indicating a younging direction to the west (Figure GS-3-4d).

The upper portion of the unit is dominated by a heterolithic tuff breccia containing light brown clasts (possibly silicified basalt, 5%, 1–3 cm, subrounded), amygdaloidal basalt clasts (35%, ≤15 cm, amoeboid), aphyric basalt clasts (10%, ≤10 cm, flattened parallel to bedding) and scoriaceous clasts (5–10%, ≤5 cm, amoeboid). There are minor tuff beds that are strongly silicified, approximately 1 m thick and interbedded with lapilli tuff beds (1–15 cm thick). Normally graded beds suggest that the unit is younging to the west.

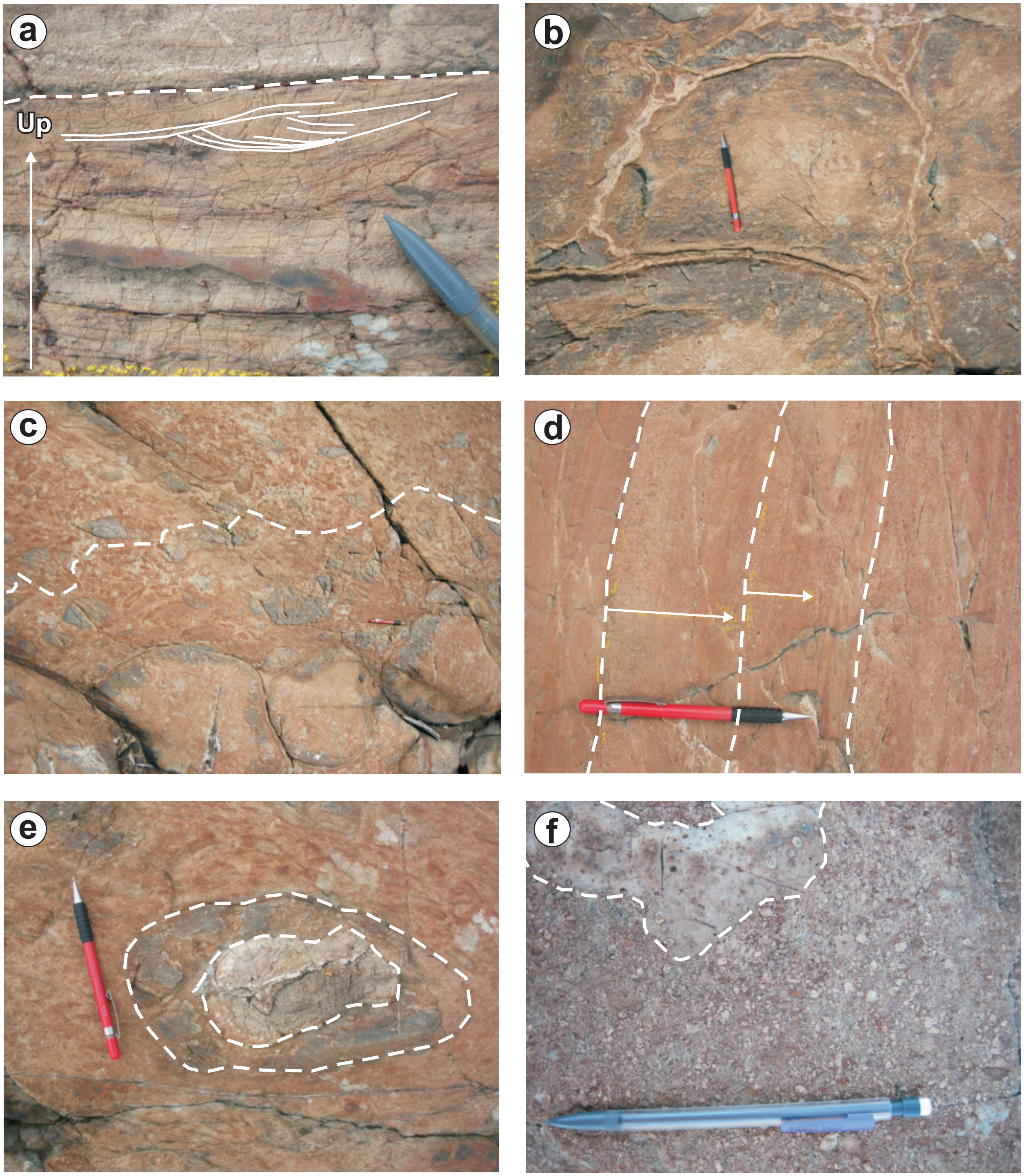



***Figure GS-3-6:*** *Photographs of rocks of the Hidden formation, Schist Lake–Mandy mines area:* ***a)*** *crosslaminated mafic tuff (laminations outlined in white; dashed white line marks contact with overlying bed);* ***b)*** *amygdaloidal, aphyric pillowed basalt;* ***c)*** *contact (dashed white line) between amoeboid, flow-top breccia and base of overlying pillowed basaltic flow;* ***d)*** *normally graded mafic tuff beds (dashed white lines mark the bases of beds);* ***e)*** *quartz-epidote–altered basalt clast rimmed or armoured by aphyric basalt;* ***f)*** *scoriaceous basalt clast (dashed white line) in plagioclase crystal–rich mafic tuff.*

Where the sill is absent, the base of the heterolithic volcaniclastic unit is defined by a 15 m thick tuff that has a conformable contact with the underlying pillowed basalts. In the underlying basalt, the pillows are brecciated and are mixed with tuff at the contact. The upper contact is not exposed (Figure GS-3-5).

#### Heterolithic volcaniclastic unit with armoured lapilli

The heterolithic volcaniclastic unit with armoured lapilli (i.e., clasts rimmed by fine-grained basalt) occurs as a discrete bed (~25 m thick) within the mafic volcaniclastic unit (Figures GS-3-4, -5).

The unit is a crudely bedded, heterolithic tuff breccia containing armoured blocks and lapilli. Clasts consist of amygdaloidal basalt (80%, 1–65 cm, rounded to amoeboid; Figure GS-3-6e), finely laminated tuff (10%, 4–40 cm, rectangular blocks) and aphyric rhyolite (10%, 1–20 cm, subangular to rounded). All clast types may be armoured, or rimmed, by <1 to 8 cm of aphyric amygdaloidal basalt. The matrix is very fine grained mafic tuff containing plagioclase crystals (5%, ≤1 mm, angular).

The lower contact with the mafic volcaniclastic unit is marked by a gabbroic intrusion or covered by overburden. The upper contact is marked by a 3–40 m thick, pillowed basaltic flow.

#### Plagioclase crystal–rich mafic volcaniclastic unit

The plagioclase crystal–rich, mafic volcaniclastic unit occurs stratigraphically above the heterolithic volcaniclastic rocks (Figures GS-3-4, -5) and is approximately 300 m in thickness. This is a minimum estimate of thickness, as the unit ends to the west in overburden against an interpreted north-trending strike-slip fault (Figure GS-3-3).

The unit is dominantly massive, with bedding only locally observed. It comprises beds of tuff breccia, lapillistone, tuff and crystal-rich lapilli tuff. The tuff-breccia beds contain clasts of scoria (10–20%, 1–30 cm, rounded to amoeboid; Figure GS-3-6f), aphyric basalt (10–20%, 1–5 cm, subrounded) and amygdaloidal basalt (10%, 1–40 cm, rounded) in a matrix of plagioclase crystal–rich (10–30%, <1–3 mm, angular to rounded), reddish brown tuff. Locally, there are light brown aphyric clasts that may be either rhyolitic or strongly silicified basalt.

Lapillistone beds in this unit are crystal rich, containing up to 40% large (1–10 mm), angular to rounded plagioclase crystals. These beds are 1–2 m thick and contain clasts of amygdaloidal to scoriaceous aphyric basalt (30%, 1–20 cm, rounded), aphyric basalt (10%, 1–4 cm, elongate parallel to bedding), and plagioclase and pyroxene porphyritic basalt (10–20%, 1–20 cm, rounded).

The lapilli-tuff beds are rare, <1 m thick and massive, containing up to 70% plagioclase crystals and basalt lapilli (10–20%) in a fine-grained tuff matrix.

The lower contact of the plagioclase crystal–rich mafic volcaniclastic unit is not exposed, and the upper contact is marked by a fault that is interpreted to lie within 100–300 m of overburden in a north-south orientation just west of Carlisle Lake.

### *Mandy Road anticline area*

The Mandy Road anticline is located approximately 1 km north of Carlisle Lake (Figure GS-3-3) and was first described as an anticline by Stockwell (1960). Detailed mapping at 1:2000 scale of the nose of the anticlinal structure during this past field season has identified three main volcanic units that can be used to better understand this structure: green aphyric basaltic flows and breccia, brown aphyric basaltic flows, and mafic volcaniclastic rocks (Figure GS-3-7). This section describes in detail each of these units and their distribution.

#### Green aphyric basaltic flows and breccia

Dark green, aphyric basalt flows occur on the western limb of the Mandy Road anticline just east of the Ross Lake Fault and in the nose of the fold. The unit is approximately 160 m thick, trends north and faces east on the western limb, and trends west and faces north in the nose of the fold (Figure GS-3-7).

The unit contains massive, pillowed and breccia facies. All facies are strongly foliated, with two cleavages observed: a more dominant one at ~335°/55°E and less dominant one at ~005°/60°E. The unit also contains numerous north-trending shear zones.

Pillowed flows dominate this unit, making up approximately 70% by volume. Pillows range in size from 0.5 to 2.5 m (with a strong north-south structural flattening); are amygdaloidal (quartz-filled, <30%, <1–15 cm); and have 1–3 cm wide, fine-grained, dark green chilled margins. Strong quartz-epidote alteration is common along the margins and in the cores of the pillows. Pillow rims and flow tops are strongly silicified locally (Figure GS-3-8a).

The massive facies contains up to 30% quartz-filled amygdules (<15 cm in diameter, averaging 3 cm) and commonly grades, in all directions, into pillows forming massive zones within pillowed flows. These zones are interpreted to represent megapillows. There are only two thin (1–2 m thick) massive flows, which are separated by a thin pillowed flow and together make up <5% of the unit.

Breccia facies are common, making up 25% of the unit. Both pillowed and massive facies grade upwards or along strike into breccias. Where the breccias define flow tops, the massive or pillowed facies gradually become brecciated over ~1 m, and the breccias are characterized by tightly packed, fluidal, aphyric basalt clasts (ranging from <1 to 30 cm) with fine-grained chilled margins in a fine-grained, dark green matrix.

On the east limb of the fold, there is a breccia within the green basaltic unit that does not define a flow top but is thicker than a flow-top breccia (35 m) and has a strike length of 60 m. This breccia is characterized by fluidal, aphyric, amygdaloidal basalt clasts (ranging from <0.01 to 1 m) with fine-grained, dark brown chilled margins that

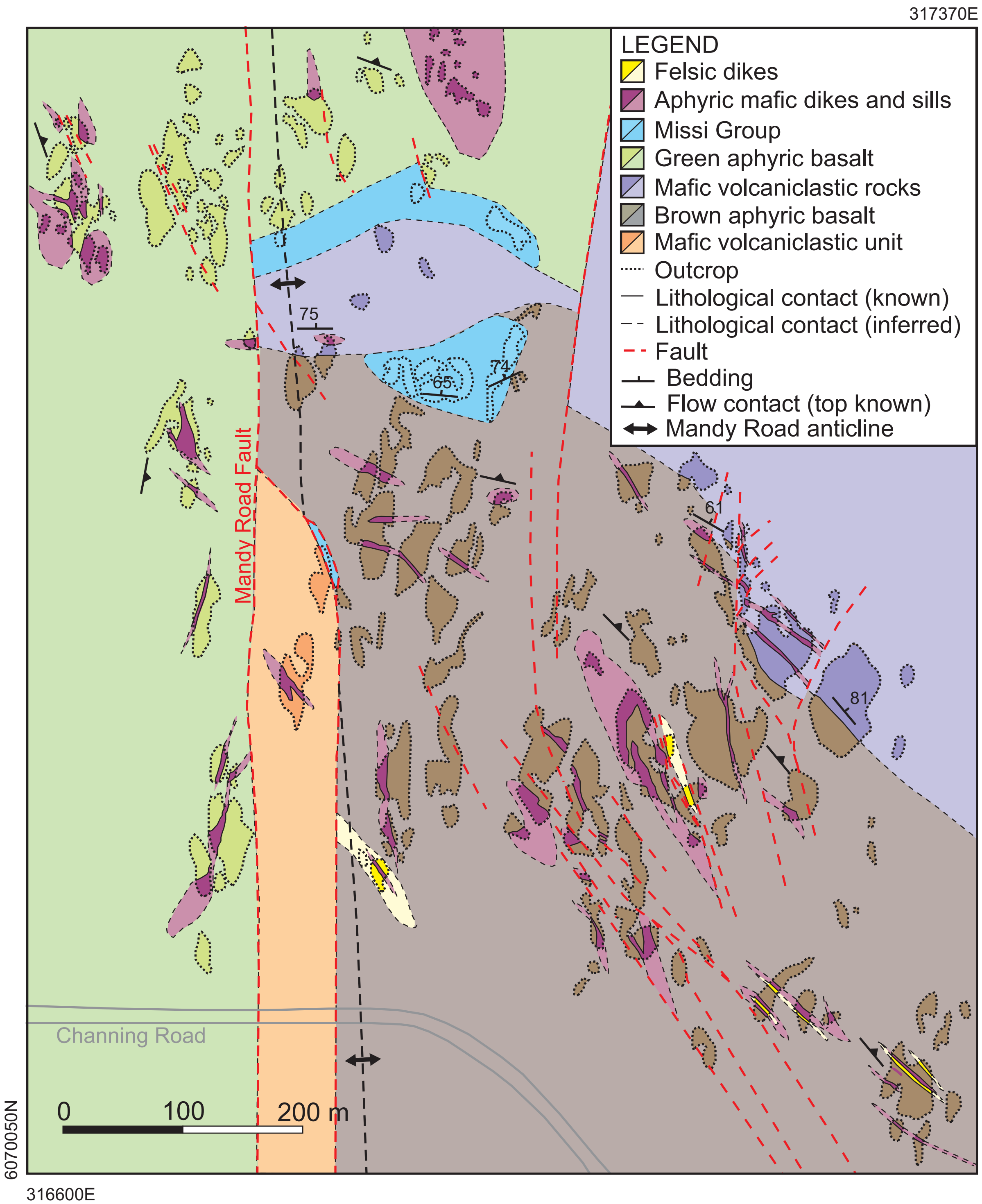



***Figure GS-3-7:*** *Detailed geology of the Hidden formation in the area of the Mandy Road anticline.*

are commonly broken. Larger clasts have strongly quartz-epidote–altered rims, and the smaller clasts are pervasively altered to quartz and epidote. Within the breccia 'pile' are zones of unbroken pillows or lobes that have strongly quartz-epidote–altered cores and/or rims. The pillows or lobes display concentric cooling laminations and 1–2 cm thick selvages, and are quartz amygdaloidal (<5%, 1–4 cm; Figure GS-3-8b).

**Brown aphyric basaltic flows**

This unit occurs in the nose and on the east limb of the Mandy Road anticline, and its exposed thickness is approximately 280 m. It is not observed on the west limb of the anticline. The upper contact is conformable and gradational over <30 cm from a pillow or flow-top breccia to a mafic volcaniclastic unit. The lower contact of this unit lies outside the map area to the south, so was not

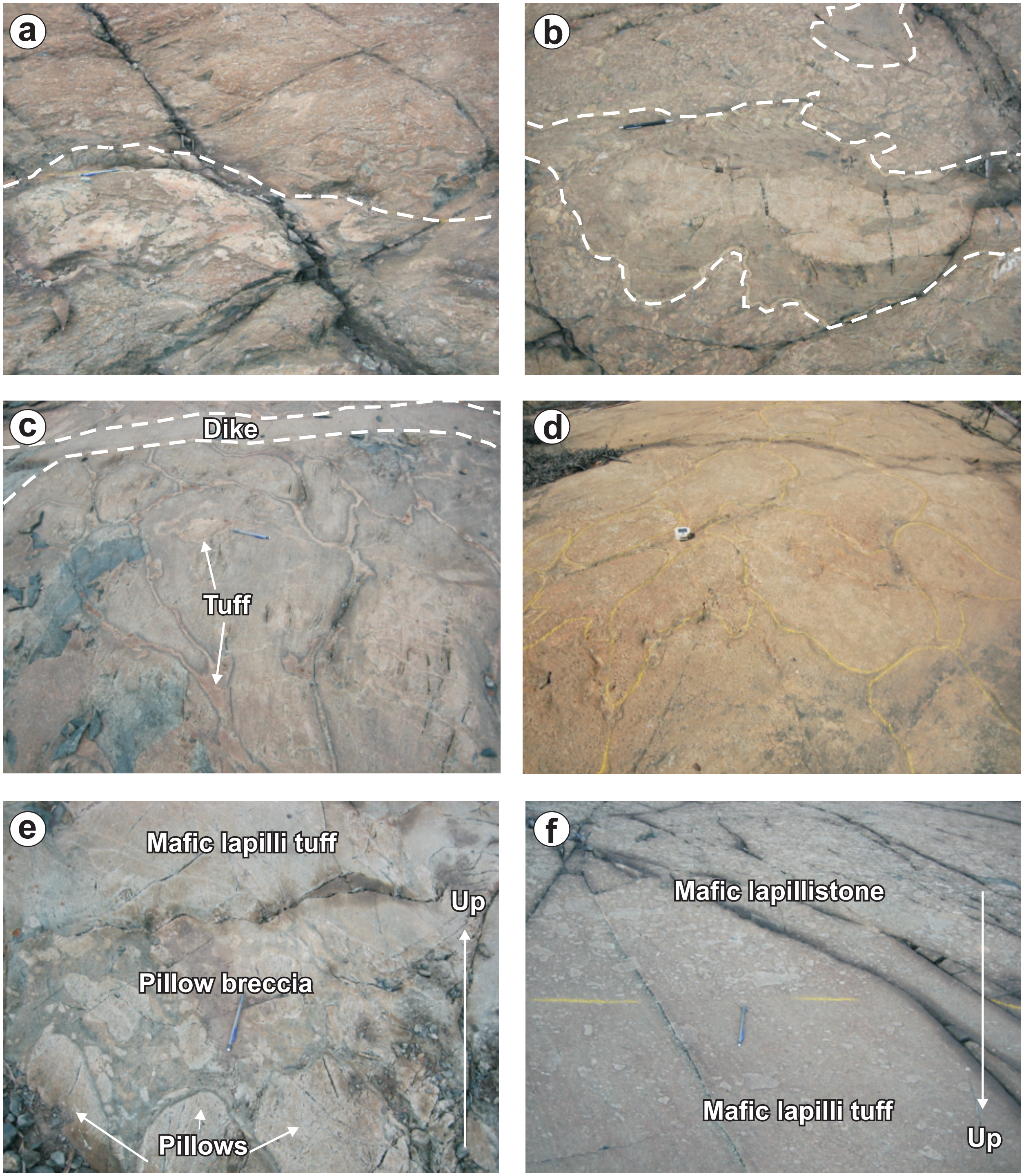



***Figure GS-3-8:*** *Photographs of rocks of the Hidden formation, Mandy Road anticline area:* ***a)*** *contact (dashed white line) between silicified pillowed basalt flow and its flow-top breccia;* ***b)*** *quartz-epidote–altered basaltic pillows or lobes within basaltic breccia pile; note unbroken chilled margin or selvage on larger pillow/lobe;* ***c)*** *pillowed basaltic flow with quartz-epidote–altered tuff between and included within pillows;* ***d)*** *pillowed flow;* ***e)*** *flow-top breccia or pillow breccia at the top of the pillowed flow shown in (c), overlain by mafic lapilli tuff;* ***f)*** *mafic lapillistone grading upwards into mafic lapilli tuff.*

observed. Future mapping (summer 2010) to the south of the Mandy Road anticline, across the Channing road, will determine how far this unit extends to the south and how it relates to the units observed in the Schist Lake–Carlisle Lake section described above. Although the Schist Lake–Carlisle Lake section is dominated by volcaniclastic rocks, Simard (2006) documented an abrupt transition from mainly volcaniclastic rocks in the south to mainly basaltic flows in the north across a potential synvolcanic fault/graben structure just east of Carlisle Lake.

This unit is dominated by pillowed, weakly plagioclase (<3%, <1 mm)– and pyroxene (<2%, <1 mm)–phyric basalt. Pillows are 0.3–3 m in diameter (average ~0.7 m) and amygdaloidal (1–50%, <2 mm), and have selvages that are 1–3 cm wide and commonly dark reddish brown with rarely a green quartz-epidote–altered middle (Figure GS-3-8c, d). The cores of pillows are strongly to weakly quartz-epidote altered, but overall alteration is less intense than that observed in the dark green aphyric basalts on the west limb of the anticline. The pillowed flows of this unit commonly break up over the upper 1–2 m of a flow, forming a pillow breccia or flow-top breccia defined by amoeboid or fluidal basalt fragments (ranging from <1 to 50 cm) with chilled margins that are tightly packed in a fine-grained reddish brown matrix. In some cases, the pillowed flows are overlain by mafic volcaniclastic rocks (Figure GS-3-8e).

#### Mafic volcaniclastic unit

A mafic volcaniclastic unit, ranging from tuff breccia to tuff, overlies the brown basalt unit that occurs in the nose and on the east limb of the Mandy Road anticline. This upper volcaniclastic unit has a minimum thickness of 60 m. There is also a lower volcaniclastic unit that occurs between pillowed flows within the core of the anticline.

The estimate of thickness for the upper volcaniclastic unit is a minimum because its upper contact with Missi Group sedimentary rocks is covered by overburden. The lower contact with underlying pillowed basalts is conformable and gradational over <30 cm. The lower volcaniclastic unit has a sheared upper contact with the overlying basalt flow and its lower contact is not exposed.

The upper volcaniclastic unit is massively bedded (metre scale) and fines upwards from tuff breccia to lapillistone to lapilli tuff to tuff. Some metre-scale reversely graded to normally graded beds can be observed on the northernmost exposure just east of the north-trending shear zone east of the fold nose. The base of the unit is a tuff breccia containing three types of aphyric basalt clasts, each with different amygdule contents (<5%, 10–20% or >50%). Clasts in the tuff breccia are up to 40 cm in size and are surrounded by a plagioclase crystal–rich matrix (10%, 1–3 mm, angular). Overall clast type and matrix remain the same, but clasts decrease upwards in number and size, thus forming the lapillistone, lapilli tuff and tuff (Figure GS-3-8f).

The mafic volcaniclastic unit that occurs in the core of the Mandy Road anticline is massive, moderately well sorted and contains 60% lithic clasts. The unit is a lapillistone with light grey, aphyric, amygdaloidal (10%, <1 mm), subrounded to subangular basalt clasts (1–5 cm) in a dark green, fine-grained tuff matrix.

## Discussion

### *Schist Lake–Carlisle Lake section*

The Hidden formation strata west of the East Mandy Road Fault structurally overlie the undivided volcanic rocks that host the Schist Lake and Mandy VMS deposits. Detailed mapping indicates that the formation constitutes a continuous succession that trends north, dips steeply to the east and faces west, thus confirming the findings of previous workers (Bailes and Syme, 1989; Simard, 2006; Simard and Creaser, 2007; Simard et al., 2009).

Tight ‘S’ and ‘Z’ folds within the mafic tuff west of the Schist Lake–Mandy mines road may result from drag folding associated with the north-trending Mandy Road faults (Figure GS-3-3). Further work is needed to assess the effects of the Mandy Road faults in the area. Mafic dikes within the tuff that have peperitic margins are synvolcanic and were emplaced when the tuff was wet and unconsolidated.

The thick units of mafic tuff and plagioclase crystal–rich mafic volcaniclastic rocks were transported by high-concentration mass flows and were preferentially deposited in paleotopographic lows or structural basins (Cas and Wright, 1987). The numerous synvolcanic basaltic sills and dikes within the volcaniclastic units suggest that this structural basin was also a mafic vent area and that an extensional regime dominated lower Hidden formation volcanism (Simard, 2006), as in the main Flin Flon VMS camp (as demonstrated by DeWolfe et al., 2009). If the Mandy Road faults did not cause major displacements that would have disrupted the stratigraphy, the limits of the paleograben observed near Carlisle Lake, when projected stratigraphically downward, could encompass the underlying Schist Lake and Mandy VMS deposits (Figure GS-3-3).

### *Mandy Road anticline*

The volcanic stratigraphy in the Mandy Road anticline area is dominated by pillowed flows, the products of effusive volcanism, that are overlain by volcaniclastic rocks ranging from tuff breccias to tuff beds. A volumetrically small breccia unit within the pillowed flows on the east limb of the fold is interpreted to represent minor fire fountains, or pyroclastic eruptions, in the area. The volcaniclastic rocks overlying the pillowed flows may be normally graded, reversely graded or massively bedded, and are interpreted to represent high-energy debris flows that have travelled downslope and accumulated in a topographic low or basin. Underlying the basaltic flows in the core of the Mandy Road anticline is a massive, well-sorted, mafic volcaniclastic rock that is also interpreted to represent a mass flow that was deposited into, and therefore defines, another topographic low. A lack of synvolcanic dikes and sills indicates that rocks of the Mandy Road anticline area are more distal to the volcanic vent than those in the Schist Lake–Carlisle Lake area. The volcaniclastic units suggest synvolcanic subsidence and related faulting in the area, creating an environment prospective for the formation of VMS-type mineralization.

This summer's mapping of the Mandy Road anticline area has shown that the Mandy Road anticline structure is not as simple as previously thought. The green aphyric basalt flows on what was previously interpreted as the west limb of the anticline strike north, dip to the east and face east. A north-south lineament, easily seen on airphotos, separates these strongly foliated, green aphyric basalts from a succession of brown, aphyric to weakly plagioclase-phyric basalts and mafic volcaniclastic rocks to the east (Figure GS-3-7). The units just east of the lineament strike west (310°) and face north. As the flows and volcaniclastic beds are traced around the previously interpreted anticline, the strike changes from 310° to 345°, with units younging to the east. The presence of this lineament, the change from strongly foliated rocks west of the lineament to more weakly foliated rocks east of it, and the change in younging direction across it all suggest that the Mandy Road anticline is a faulted anticline, as previously suggested by Simard and Creaser (2007). As suggested by Bailes and Syme (1989) and Simard and Creaser (2007), this lineament most likely represents a north-trending sinistral fault, likely a splay from the north-trending Mandy Road faults immediately southeast of the Mandy Road anticline, that has rotated a block (the west limb of the fold) in a clockwise direction into its current orientation.

## Future work

During the upcoming field season, the area between the Schist Lake–Carlisle Lake section and the Mandy Road anticline map area, and the area south and east of the Schist Lake–Carlisle Lake section, including the undivided volcanic rocks hosting the Schist Lake and Mandy deposits, must be mapped at 1:2000 to accurately place the location of the Mandy Road anticlinal fold axis and assess the effect of the Mandy Road faults on the stratigraphy. This work will allow for the predeformation reconstruction of the volcanic environment(s) of the rocks in the Schist Lake–Carlisle area and the Mandy Road anticline area, as well as the hostrocks of the Schist Lake and Mandy deposits. This reconstruction is essential in moving forward with exploration for base metals in the area.

## Economic considerations

The general association of volcanogenic massive sulphide (VMS) deposits with extensional environments in arcs has been well documented (e.g., Franklin et al., 1981, 2005; Sillitoe, 1982; Cathles et al., 1983; Gibson et al., 1999; Syme et al., 1999). The VMS deposits at Flin Flon are no exception and have been shown to be temporally associated with inferred arc-rifting processes (Syme et al., 1996; Bailes and Galley, 1999; Syme et al., 1999). For example, the footwall to the Flin Flon VMS deposits is dominated by thick mass-flow deposits that infill nested basins within a larger cauldron subsidence structure that is crosscut by a synvolcanic dike swarm (Gibson et al., 2003; Devine, 2003).

Although the abundance of dikes is considerably less in the Schist Lake–Carlisle Lake area, the abundance and volume of volcaniclastic deposits are comparable to those hosting the mineralization in the main Flin Flon camp. This evidence for an extensional regime within the strata that structurally overlie the rocks hosting the Schist Lake and Mandy deposits has significant economic implications. Firstly, the synvolcanic grabens in which the voluminous volcaniclastic rocks have been deposited provide pathways (synvolcanic faults that define the grabens) for hydrothermal fluids. Secondly, the volcaniclastic rocks also imply a significant hiatus in effusive volcanism, a feature conducive to the formation of VMS deposits, which typically form during volcanic hiatuses and are localized by synvolcanic faults that focus hydrothermal discharges (Gibson et al., 1999).

These rocks do contain areas of patchy, strong quartz-epidote alteration. This alteration is especially evident in pillowed basaltic flows and indicates high-temperature hydrothermal activity syn- to postemplacement of the units (MacGeehan, 1978; Gibson et al., 1983; Seyfried et al., 1988, 1999; Gibson, 1990; Franklin et al., 1994; Skirrow and Franklin, 1994; Harper, 1999; Alt, 1999; Santaguida, 1999). This alteration, combined with the interpreted extensional environment and volcaniclastic units, makes the Schist Lake–Carlisle Lake rocks an environment that is prospective for undiscovered VMS-type mineralization.

Another significant economic implication of this study is that these synvolcanic structures in the Schist Lake–Carlisle Lake area define structural corridors that, when extended downwards into the underlying rocks, could encompass the Schist Lake and Mandy VMS deposits, depending on the structural displacement along the Mandy Road faults. This suggests the longevity and reactivation of these structures, leading to the formation of the Schist Lake and Mandy deposits. Like in the main Flin Flon camp, this possible correlation suggests that synvolcanic structures in hangingwall successions of other VMS districts may be useful for targeting massive sulphide mineralization along the same structures at depth.

## Acknowledgments

Funding for this project was provided by the Geological Survey of Canada through the Targeted Geoscience Initiative 3 program. Logistical support was provided by the Manitoba Geological Survey and HudBay Minerals Inc. The author thanks J. Fell for providing enthusiastic field assistance, as well as N. Brandson for thorough logistical support. My thanks also go to H. Gibson, R-L. Simard and T. Corkery for reviewing the manuscript.

## References

Alt, J.C. 1999: Hydrothermal alteration and mineralization of oceanic crust: mineral geochemistry and processes; Economic Geology, v. 8, p. 133–155.

Bailes, A.H. and Galley, A.G. 1999: Evolution of the Paleoproterozoic Snow Lake arc assemblage and geodynamic setting for associated volcanic-hosted massive sulphide deposits, Flin Flon Belt, Manitoba, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1789–1805.

Bailes, A.H. and Syme, E.C. 1989: Geology of the Flin Flon–White Lake area; Manitoba Energy and Mines, Geological Services, Geological Report GR87-1, 313 p.

Cas, R.A.F. and Wright, J.V. 1987: Volcanic successions, modern and ancient; a geological approach to processes, products and successions; Allen & Unwin, London, United Kingdom, 544 p.

Cathles, L.M., Guber, A.L., Lenagh, T.C. and Dudàs, F.Ö. 1983: Kuroko-type massive sulphide deposits of Japan: products of an aborted island-arc rift; Economic Geology, Monograph 5, p. 96–114.

Cole, E.M., Piercey, S.J. and Gibson, H. L. 2008: Geology and geochemistry of the Schist Lake mine area, Flin Flon, Manitoba (part of NTS 63K12); *in* Report of Activities 2008, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 18–28.

Cole, E.M., Gibson, H.L. and Lafrance, B. 2007: Preliminary description of the lithofacies and structure of the Schist Lake mine area, Flin Flon, Manitoba (part of NTS 63K12); *in* Report of Activities 2007, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 33–42.

Devine, C.A. 2003: Origin and emplacement of volcanogenic massive sulphide–hosting, Paleoproterozoic volcaniclastic and effusive rocks within the Flin Flon subsidence structure, Manitoba and Saskatchewan, Canada; M.Sc. thesis, Laurentian University, Sudbury, Ontario, 279 p.

Devine, C.A., Gibson, H.L., Bailes, A.H., MacLachlan, K., Gilmore, K. and Galley, A.G. 2002: Stratigraphy of volcanogenic massive sulphide–hosting volcanic and volcaniclastic rocks of the Flin Flon formation, Flin Flon (NTS 63K12 and 13), Manitoba and Saskatchewan; *in* Report of Activities 2002, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 9–19.

DeWolfe, Y.M., Gibson, H.L., Lafrance, B. and Bailes, A.H. 2009: Volcanic reconstruction of Paleoproterozoic arc volcanoes: the Hidden and Louis formations, Flin Flon, Manitoba, Canada; Canadian Journal of Earth Sciences, v. 46, p. 481–508.

Fisher, R.V. 1961: Proposed classification of volcaniclastic sediments and rocks; Geological Society of America Bulletin, v. 72, p. 1395–1408.

Franklin, J.M., Lydon, J.W. and Sangster, D.F. 1981: Volcanic-associated massive sulphide deposits; *in* Economic Geology 75th Anniversary Volume, B.J. Skinner (ed.), Economic Geology Publishing Company Inc., Littleton, Colorado, p. 485–627.

Franklin J.M., Goodfellow W.D., Davis, E.E. and Zierenberg, R.A. 1994: Site 856 of ODP leg 139: discovery of a major massive sulfide deposit on Middle Valley of the Juan de Fuca; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Abstracts Volume 19, p. 38.

Franklin, J.M., Gibson, H.L., Jonasson, I.R. and Galley, A.G. 2005: Volcanogenic massive sulfide deposits; *in* Economic Geology 100th Anniversary Volume, J.W. Hedenquist, J.F.H. Thompson, R.J. Goldfarb, and J.P. Richards (ed.), Economic Geology Publishing Company Inc., Littleton, Colorado, p. 523–560.

Gibson, H.L., Watkinson, D.H. and Comba, C.D.A. 1983: Silicification: hydrothermal alteration in an Archean geothermal system within the Amulet rhyolite formation; Economic Geology, v. 78, p. 954–971.

Gibson, H.L., Morton, R.L. and Hudak, G.J. 1999: Submarine volcanic processes, deposits, and environments favourable for the location of volcanic associated massive sulfide deposits; *in* Volcanic Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings, C.T. Barrie and M.D. Hannington (ed.), Reviews in Economic Geology, v. 8, p. 13–49.

Gibson, H., Devine, C., Galley, A., Bailes, A., Gilmore, K., MacLachlan, K. and Ames, D. 2003: Structural control on the location and formation of Paleoproterozoic massive sulphide deposits as indicated by synvolcanic dike swarms and peperite, Flin Flon, Manitoba and Saskatchewan; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Abstracts, v. 28.

Harper, G.D. 1999: Structural styles of hydrothermal discharge in ophiolite/sea-floor systems; Economic Geology, v. 8, p. 53–73.

Lucas, S.B., Stern, R.A., Syme, E.C., Reilly, B.A. and Thomas, D.J. 1996: Intraoceanic tectonics and the development of continental crust: 1.92–1.84 Ga evolution of the Flin Flon Belt, Canada; Geological Society of America Bulletin, v. 108, p. 602–629.

Lucas, S.B., Stern, R.A., Syme, E.C., Zwanzig, H., Bailes, A.H., Ashton, K.E., Maxeiner, R.O. Andsell, K.M., Lewry, J.F., Ryan, J.J. and Kraus, J. 1997: Tectonics of the southeastern Reindeer Zone, Trans-Hudson Orogen (Manitoba and Saskatchewan); Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Abstracts, v. 22, p. A93.

MacGeehan, P.J. 1978: The geochemistry of altered volcanic rocks at Matagami, Quebec: a geothermal model for massive sulfide genesis; Canadian Journal of Earth Sciences, v. 15, p. 551–570.

Santaguida, F. 1999: The paragenetic relationships of epidote-quartz hydrothermal alteration within the Noranda volcanic complex, Quebec; Ph.D. thesis, Carleton University, Ottawa, Ontario, 302 p.

Seyfried, W.E., Berndt, M.E. and Seewald, J.S. 1988: Hydrothermal alteration processes at mid-ocean ridges: constraints from diabase alteration experiments, hot-spring fluids and composition of the oceanic crust; Canadian Mineralogist, v. 26, p. 787–804.

Seyfried, W.E., Ding, K., Berndt, M.E. and Chen, X. 1999: Experimental and theoretical controls on the composition of mid-ocean ridge hydrothermal fluids; Economic Geology, v. 8, p. 181–200.

Sillitoe, R.H. 1982: Extensional habitats of rhyolite-hosted volcanogenic massive sulphide deposits; Geology, v. 10, p. 403–407.

Simard, R-L. 2006: Geology of the Schist Lake–Mandy mines area, Flin Flon, Manitoba (part of NTS 63K12); *in* Report of Activities 2006, Manitoba Science Technology, Energy and Mines, Manitoba Geological Survey, p. 9–21.

Simard, R-L. and Creaser, R.A. 2007: Implications of new geological mapping, geochemistry and Sm-Nd isotope data, Flin Flon area, Manitoba (part of NTS 63K12); *in* Report of Activities 2007, Manitoba Sciences, Technology, Energy and Mines, Manitoba Geological Survey, p. 7–20.

Simard, R.L., Kremer, P.D., MacLachlan, K., DeWolfe, Y.M., Gibson, H.L., Devine, C., Lafrance, B., Ames, D., Price, D.P. and Pehrsson, S. 2007: Geology of the Flin Flon area, Manitoba (part of NTS 63K12); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Preliminary Map PMAP2007-1, scale 1:10 000.

Simard, R-L., MacLachlan, K., Gibson, H.L., DeWolfe, Y.M., Devine, C., Kremer, P.D., Lafrance, B., Ames, D.E., Syme, E.C., Bailes, A.H., Bailey, K., Price, D., Pehrsson, S., Cole, E., Lewis, D. and Galley, A.G. 2009: Geology of the Flin Flon area, Manitoba and Saskatchewan (part of NTS 63K12, 13); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2009-1 and Saskatchewan Energy and Resources, Geoscience Map 2009-1, scale 1:10 000.

Skirrow, R.G. and Franklin, J.M. 1994: Silicification and metal leaching in semiconformable alteration beneath the Chisel Lake massive sulfide deposit, Snow Lake, Manitoba; Economic Geology, v. 89, p. 31–50.

Stern, R.A., Syme, E.C., Bailes, A.H. and Lucas, S.B. 1995: Paleoproterozoic (1.90–1.86 Ga) arc volcanism in the Flin Flon belt, Trans-Hudson Orogen, Canada; Contributions to Mineralogy and Petrology, v. 119, p. 117–141.

Stern, R.A., Machado, N., Syme, E.C., Lucas, S.B. and David, J. 1999: Chronology of crustal growth and recycling in the Paleoproterozoic Amisk collage (Flin Flon Belt), Trans-Hudson Orogen, Canada; Canadian Journal of Earth Sciences, v. 36, p. 1807–1827.

Syme, E.C. and Bailes, A.H. 1993: Stratigraphy and tectonic setting of Early Proterozoic volcanogenic massive sulphide deposits, Flin Flon, Manitoba; Economic Geology, v. 88, p. 566–589.

Stockwell, C.H. 1960: Flin Flon–Mandy, Manitoba and Saskatchewan; Geological Survey of Canada, Map 1078A, scale 1:12 000.

Syme, E.C., Bailes, A.H., Lucas, S.B. and Stern, R.A. 1996: Tectonostratigraphic and depositional setting of Paleoproterozoic volcanogenic massive sulphide deposits, Flin Flon Belt, Manitoba; Geological Association of Canada–Mineralogical Association of Canada Joint Annual Meeting, Abstracts, v. 21, p. A93.

Syme, E.C., Lucas, S.B., Bailes, A.H. and Stern, R.A. 1999: Contrasting arc and MORB-like assemblages in the Paleoproterozoic Flin Flon Belt, Manitoba, and the role of intra-arc extension in localizing volcanic-hosted massive sulphide deposits; Canadian Journal of Earth Sciences, v. 36, p. 1767–1788.

White, J.D.L. and Houghton, B.F. 2006: Primary volcaniclastic rocks; Geology, v. 34, p. 677–680.

White, J.D.L., McPhie, J. and Skilling, I. 2000: Peperite: a useful genetic term; Bulletin of Volcanology, v. 62, p. 65–66.