GS2017-7

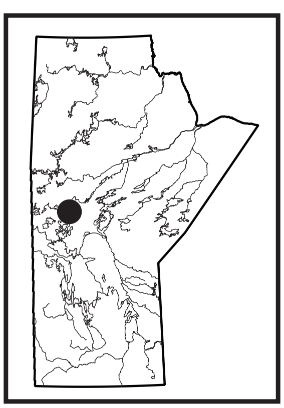
Sub-Phanerozoic basement geology south of Wekusko Lake, eastern Flin Flon belt, north-central Manitoba (parts of NTS 63J5, 12, 63K8, 9): insights from drillcore observations and whole-rock geochemistry of mafic rocks

by K.D. Reid

In Brief:

- Basaltic rocks south of Wekusko Lake are chemically analogous to modern juvenile arc and mid-ocean ridge basalts
- Prospective stratigraphy, including felsic volcanic rocks, extends along strike from the Kofman deposit
- Mafic volcanic associations locally contain orogenic-style gold mineralization

Citation:
Reid, K.D. 2017: Sub-Phanerozoic basement geology south of Wekusko Lake, eastern Flin Flon belt, north-central Manitoba (parts of NTS 63J5, 12, 63K8, 9): insights from drillcore observations and whole-rock geochemistry of mafic rocks; *in* Report of Activities 2017, Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, p. 65–77.



Summary

Twenty-five historical exploration drillcores from the area south and east of Wekusko Lake were re-examined over a three-week period in the summer of 2017. Data from 20 of these drillcores were combined with data from 18 drillcores examined during the 2016 field season to provide wide-spaced coverage over a large area south of Wekusko Lake, roughly equivalent to a 1:50 000 map area. This work is part of a broader project to create a series of 1:50 000 scale maps for the eastern portion of the sub-Phanerozoic Flin Flon belt. These maps will provide new data to constrain poorly understood geology and better inform exploration models. Four drillcores from east of the current study area facilitated a preliminary investigation of the geology in the adjacent map sheet, whereas the review of one drillcore from the Watts River volcanogenic massive-sulphide (VMS) deposit allowed examination of hostrocks and the collection of one sample for U-Pb dating. The objectives of this season's fieldwork were to 1) document the rock types in the eastern and southern portions of the map area; 2) obtain additional whole-rock geochemical data for volcanic and plutonic rocks not covered by previous regional compilations in order to facilitate correlations; and 3) identify samples suitable for U-Pb dating within both volcanic and sedimentary sequences.

Introduction

The Flin Flon belt (FFB) consists of a series of oceanic assemblages that were formed and tectonically juxtaposed during closure of the Proterozoic Manikewan Ocean (e.g., Stauffer, 1984; Syme and Bailes, 1993), and is one of a series of belts that make up the internal Reindeer zone of the Paleoproterozoic Trans-Hudson orogen (Lewry and Collerson, 1990). Volcanic assemblages (ca. 1.9–1.8 Ga) include juvenile island-arc, juvenile ocean-floor/back-arc, and ocean-island basalt (Syme et al., 1999). Following the accretion of oceanic volcanic assemblages was the emplacement of 'successor'-arc plutons (1.87–1.83 Ga; e.g., Whalen et al., 1999). Fluvial-alluvial sandstone and conglomerate of the Missi group (1.85–1.83 Ga) unconformably overlie older volcanic rocks (e.g., Ansdell et al., 1992; Syme et al., 1999). Burntwood group (1.85–1.84 Ga) greywacke and argillite is considered the lateral facies equivalents to the Missi group (e.g., Ansdell et al., 1995).

The FFB is one of the most prolific volcanogenic massive-sulphide (VMS)–hosting greenstone belts in the world, with the majority of deposits hosted by arc and arc-rift volcanic sequences (Syme et al., 1999). Exploration in the FFB has matured from prospecting in the exposed portions to deep-penetrating airborne geophysical surveys coupled with diamond drilling in areas with little or no exposure. Airborne geophysical surveys (magnetic and electromagnetic) flown within the past 25 years can resolve differences in magnetic susceptibility and conductivity beneath as much as 300 m of cover, allowing exploration to proceed in areas overlain by Phanerozoic strata. As a result, several VMS deposits have been discovered beneath Phanerozoic cover since the mid 1990s. However, when plotted on existing geological maps, several of these VMS deposits coincide with areas identified as being predominantly sedimentary, such as the East Kisseynew domain (e.g., Watts River, Harmin, Fenton and Talbot deposits; Figure GS2017-7-1), rather than being associated with volcanic domains similar to those that host major VMS deposits in the exposed portion of the FFB. This has brought into focus the need for updated geological maps for the sub-Phanerozoic portion of the eastern FFB. A new mapping program involving re-examination of exploration drillcore and compilation of geochemical and geophysical data is currently underway to facilitate a better understanding of the basement geology in the covered portion of the FFB and its economic potential.

Previous work in the south Wekusko Lake area

The eastern FFB includes both exposed and sub-Phanerozoic portions (Figure GS2017-7-1). The exposed portion is subdivided into tectonostratigraphic assemblages on the basis of bedrock

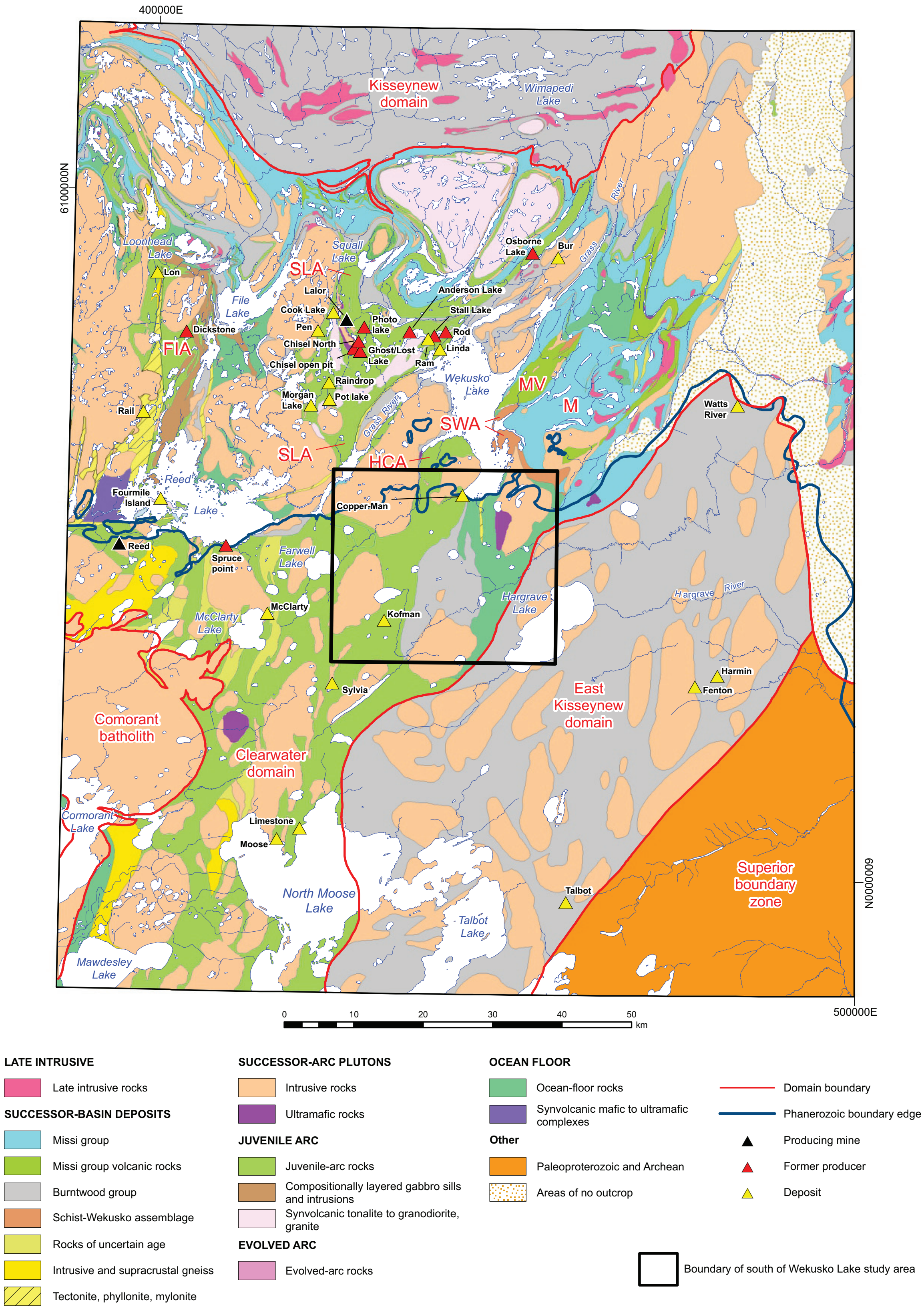


Figure GS2017-7-1: *Generalized geology of the exposed and sub-Phanerozoic eastern Flin Flon belt, showing major tectonostratigraphic assemblages/domains and volcanogenic massive-sulphide deposits (modified from Leclair and Viljoen, 1997; NATMAP Shield Margin Project Working Group, 1998). Box outlines the south Wekusko Lake study area in GS2017-7-2. Exposed tectonostratigraphic assemblages: FIA, Fourmile Island assemblage; HCA, Hayward Creek assemblage, M, Missi group; MV, Missi group volcanic rocks; SLA, Snow Lake assemblage; SWA, Schist-Wekusko assemblage. Thick red lines define sub-Phanerozoic domains.*

mapping (e.g., Syme et al., 1995; Bailes and Galley, 2007) whereas Leclair et al. (1997) subdivided the sub-Phanerozoic portion into three domains on the basis of geophysical mapping: the Cormorant batholith, the Clearwater domain and the East Kisseynew domain (GS2017-7-1). The Clearwater domain consists of relatively lower grade (greenschist to lower-amphibolite facies) volcanic rocks that vary in composition from mafic to felsic and include different depositional facies. Farther east in the East Kisseynew domain, the metamorphic grade increases dramatically to upper-amphibolite facies, such that primary textures are obscured and protolith identification is difficult. Nevertheless, this domain is thought to consist of highly recrystallized Burntwood group turbidites and plutons (Figure GS2017-7-1).

Figure GS2017-7-2 shows the simplified geology of the exposed portion of the eastern FFB based on mapping (e.g., Gilbert and Bailes, 2005; Bailes and Galley, 2007). Gilbert and Bailes (2005) described the geology of the southern half of Wekusko Lake and outlined five tectonostratigraphic blocks from west to east: 1) Hayward Creek assemblage of juvenile-arc affinity; 2) Burntwood group turbidites; 3) South Wekusko assemblage of ocean-floor affinity; 4) Schist-Wekusko assemblage of successor-arc affinity; and 5) Missi group sandstone and conglomerate (Figure GS2017-7-2). Multiple large intrusions of successor-arc age (1.87–1.83 Ga) intrude and some cases stitch the stratigraphic assemblages.

The Hayward Creek assemblage, consisting of arc-volcanic, intrusive and sedimentary rocks, forms a lozenge south of Goose Bay and is bounded to the west by Hayward Creek before extending south beneath Phanerozoic cover (Figure GS2017-7-2). The age of the Hayward Creek assemblage is uncertain but it has many similarities to the Snow Lake assemblage (Gilbert and Bailes, 2005). At the core of the Hayward Creek assemblage is the Southwest Wekusko Lake pluton, which varies from granodiorite to diorite (Figure GS2017-7-2).

Burntwood group greywacke and mudstone, interpreted to be in thrust contact with the Hayward Creek assemblage, is observed along the western shoreline (and on some islands) of Wekusko Lake near Goose Bay. At the southern end of Wekusko Lake, a package, <1 km wide at the lakeshore, widens and extends approximately 25 km to the south (Figure GS2017-7-2).

East of the Burntwood group at the south end of Wekusko Lake is a sequence of pillowed basalt flows and related gabbro sills, which are geochemically akin to the 1.90 Ga Elbow-Athapapuskow and Northeast Reed ocean-floor basalt assemblages (Stern et al., 1995b; Syme et al., 1995). These rocks are termed the South Wekusko assemblage by Gilbert and Bailes (2005).

The Crowduck Bay fault is a crustal-scale fault that can be traced to the north of Broad Bay before trending northeast in Crowduck Bay (Figure GS2017-7-2). Toward the north, it separates Burntwood group turbidites from Schist-Wekusko assemblage successor-arc volcanic rocks, and younger Missi group volcanic and sedimentary rocks (Connors and Ansdell, 1994; Ansdell et al., 1999; Gilbert and Bailes, 2005). At the south end of Wekusko Lake, the Crowduck Bay fault is a phyllonitic package of chlorite-carbonate schist within the South Wekusko assemblage, and extends beneath the Phanerozoic cover (Figure GS2017-7-2).

Drillcore examination

Twenty-five historical exploration drillcores from the area south and east of Wekusko Lake were re-examined over a three-week period in the summer of 2017. Data from these historical exploration drillcores were combined with data from 18 drillcores examined during the 2016 field season (Reid and Gagné, 2016). Drillcore observations from 25 of these drillholes are discussed with reference to the Clearwater and East Kisseynew domains (Leclair et al., 1997; Figures GS2017-7-1, -2). Clearwater domain rocks are subdivided into four lithological associations: bimodal volcanic; mafic-dominated; plutonic; and sedimentary. Only bimodal volcanic, mafic-dominated and plutonic associations are described in this report. Due to heterogeneity between drillcores, rocks of the East Kisseynew domain are not presently subdivided.

Drillholes near the western edge of the study area in the Clearwater domain, which were examined by Gagné (2015, GS2017-9, this volume), are briefly mentioned and shown in Figure GS2017-7-2.

Clearwater domain

Bimodal volcanic association

Drillcores CP-11-017, 94-15 and SL91-7 (Assessment files 63J1159, 72778, 72326, Manitoba Growth, Enterprise and Trade, Winnipeg) all contain significant intervals (25–100 m) of weakly to moderately strained, intermediate to felsic volcaniclastic rocks (crystal tuff to heterolithic tuff breccia) that show moderate pervasive epidote-silica and local discordant chlorite-carbonate alteration (Figure GS2017-7-3a, b).

The upper half (94.7–247.3 m) of drillcore CP-11-017 is a thick sequence of moderately to strongly foliated quartz-phyric dacite, which is separated from heterolithic lapilli tuff in the lower part of the drillcore (320.0–422.8 m) by a package of graphitic greywacke and argillite (247.3–320.0 m). Between 372.7 and 403.0 m a fine- to medium-grained, leucocratic granodiorite is present. The last two metres of the drillcore (422.8–425.0 m) is a moderately foliated, equigranular, medium-grained mesocratic gabbro.

The upper portion of drillcore 94-15 is a massive, dark green, aphanitic basalt flow that contains scattered 0.2–1 cm quartz amygdules before gradationally becoming a heterolithic breccia (the mafic matrix of the breccia also contains amygdules—flow-top breccia, intrusion breccia or peperite?) at 102.0 m. The heterolithic breccia contains angular, light grey, aphanitic, felsic fragments (20%; 1–15 cm) and subangular epidote-altered mafic fragments (30%; 2–10 cm) in a silicified feldspar-pyroxene crystal tuff matrix. This breccia grades into a thick sequence (128–195.5 m) of intermediate to felsic ash tuff/greywacke, which contains local centimetre-scale seams of pyrite and graphite, the lower contact to this unit is marked

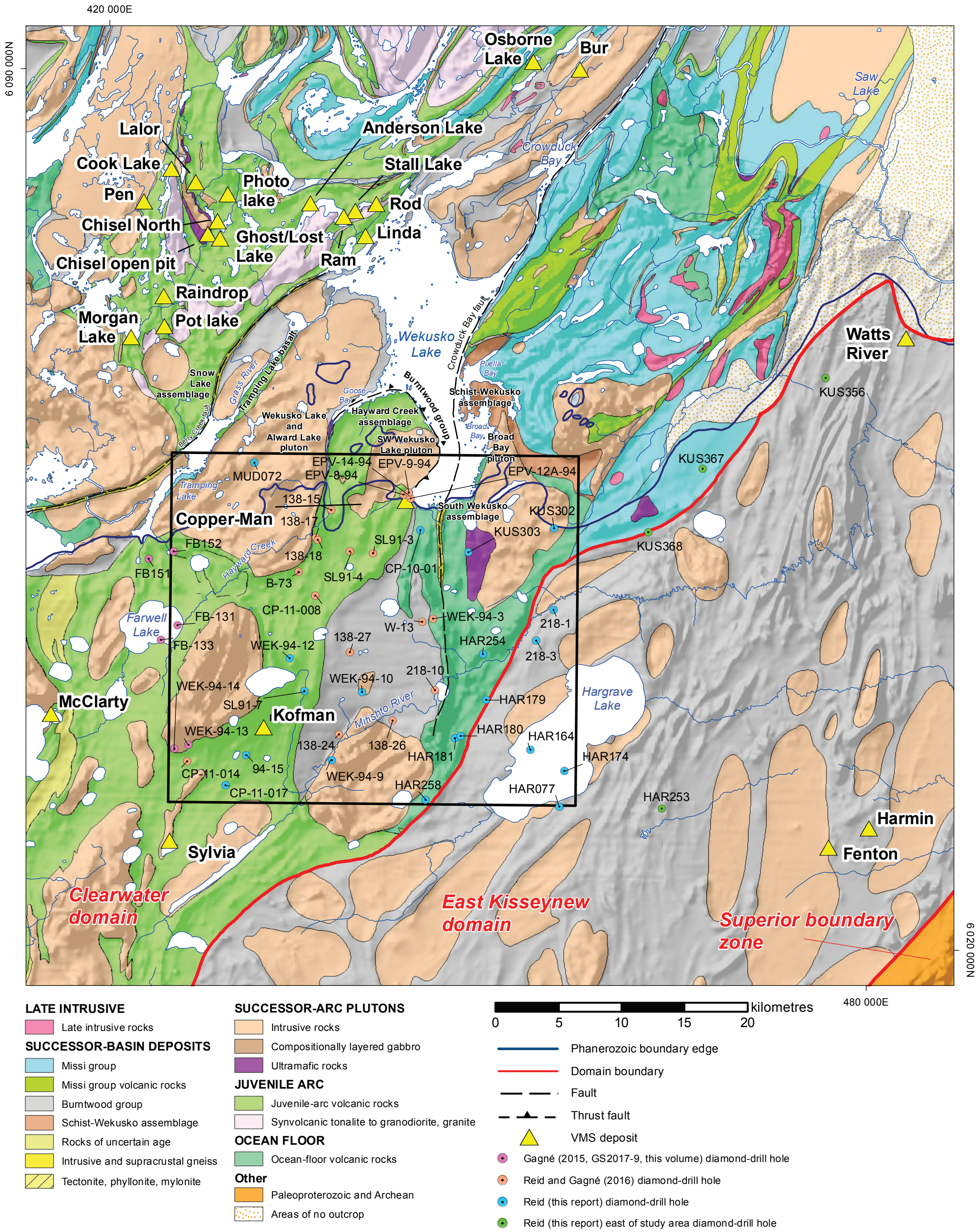


Figure GS2017-7-2: *Geology of the south Wekusko Lake area (modified from NATMAP Shield Margin Project Working Group, 1998), showing the collar locations discussed in this report. Abbreviation: SW, Southwest.*

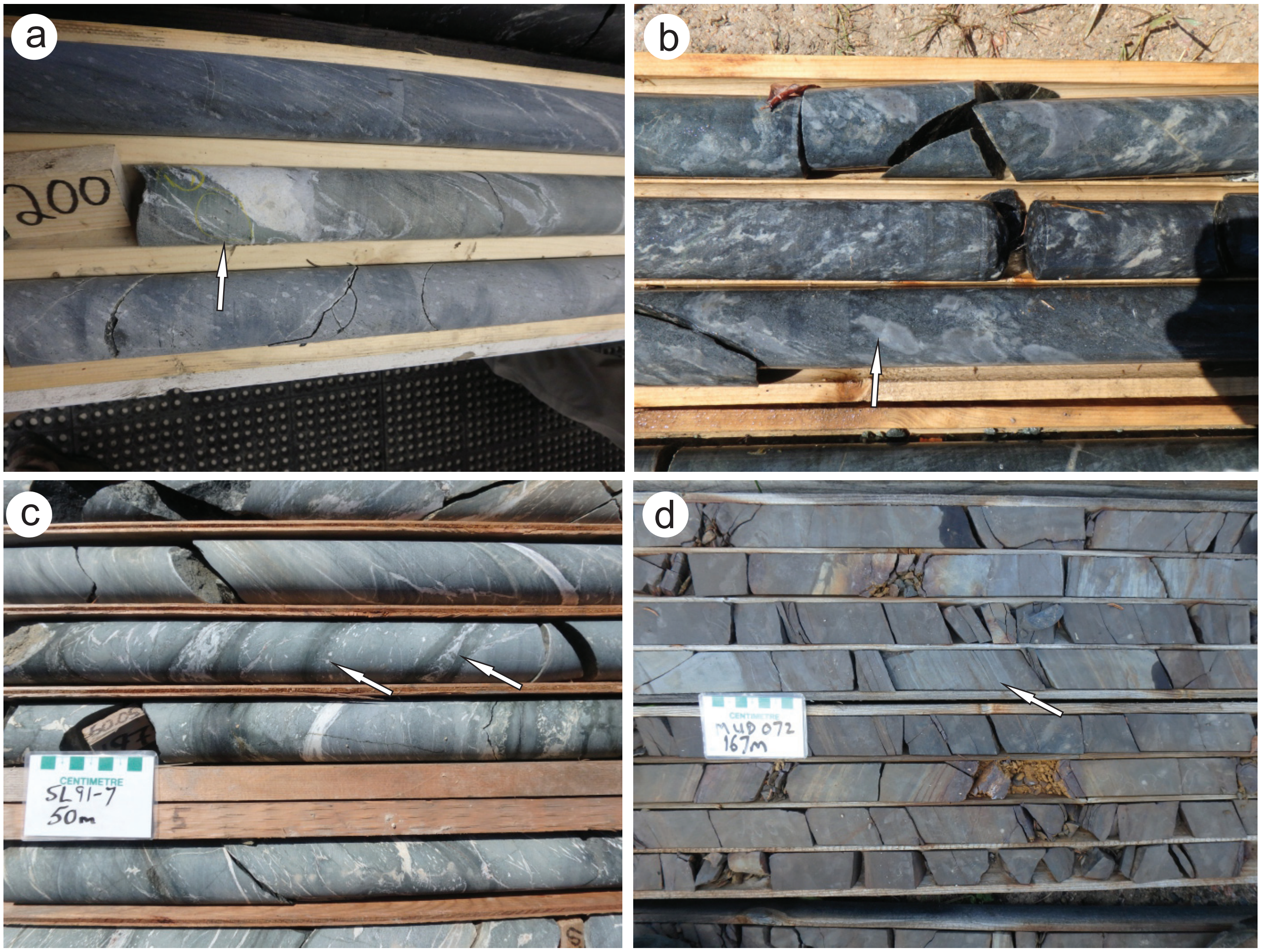


Figure GS2017-7-3: *Volcanic rocks of various composition in the Clearwater domain:* ***a)*** *wispy domains of chlorite-carbonate with trace specks of chalcopyrite (arrow) cutting mafic rocks that are adjacent to quartz-eye dacite, drillcore CP-11-017, 200.0 m, NQ;* ***b)*** *angular felsic fragments (arrow) in a epidote-silica–altered matrix, drillcore 94-15, 124.5 m, NQ;* ***c)*** *pillow basalt with carbonate amygdules and dark green selvages (right arrow), drillcore SL91-7, 50.0 m, NQ;* ***d)*** *laminated tuff/graphitic argillite with weak zinc-copper mineralization (arrow), drillcore MUD072, 167.0 m, BQ. Core diameter: NQ, 4.76 cm; BQ, 3.65 cm.*

by the appearance of angular blocks of rhyolite (5–20 cm) that have very distinctive 1–8 mm blue quartz phenocrysts. The blue quartz–porphyritic fragmental rhyolite and massive rhyolite extend to the end of the hole (227.0 m). Well-preserved pillowed mafic flows, which have calcite amygdules around the pillow margins, dark green selvages and interpillow hyaloclastite, occur between 43.0 and 75.2 m in drillcore SL91-7 (Figure GS2017-7-3c). Thinly laminated graphitic argillite (75.2–82.6 m) grades into intermediate lapilli tuff (82.6–109.0 m) that is intruded by equigranular, medium-grained gabbro in drillcore SL91-7.

The WEK-94-12 (Assessment File 94654) is a short drillcore (125 m) that intersects dark grey–black, aphanitic to fine-grained rock of mafic composition (59.9–125 m); aside from grain-size decreasing downhole, it contains no textural clues to indicate whether it is an extrusive volcanic or a hypabyssal intrusion.

Drillhole MUD072 (Assessment File 74711) is collared in what is mapped as successor-arc intrusive rocks related to the Alward Lake pluton (Figure GS2017-7-2; NATMAP Shield Margin Project Working Group, 1998). However, the drillcore consists of several successions of intermediate feldspar-crystal lapilli tuff to crystal tuff several metres thick. Graded beds indicate that the package is overturned. At a depth of 112.3 m, a thick package (77.7 m) of thinly laminated (millimetre-scale) sulphide-graphite–bearing argillite/ash tuff is present (Figure GS2017-7-3d). The remainder of the drillcore, from 190.0 to 224.0 m, is feldspar-crystal tuff similar to that observed above the argillite.

Drillcore FB152, examined in the summer of 2015, is described as a package of amygdaloidal mafic flows (50 m thick) followed by a thick interval of heterolithic felsic tuff breccia whereas drillhole FB151 encountered mainly mafic volcaniclastic rocks (see Gagné, 2015 for more details). Descriptions of volcanic rocks observed in drillcores FB-131 and FB-133 during the 2017 field season are in this volume (Gagné, GS2017-9, this volume).

Mafic-dominated association

Drillcores CP-10-01 and KUS303 (Assessment files 74903, 74423) consist mainly of aphanitic to fine-grained, dark green basalt, which in places contains faint pillow selvages (Figure GS2017-7-4a); heterogeneous ductile deformation represented by discrete shear zones, varying from a few centimetres to several metres wide, is observed in both drillcores. Given its proximity to the inferred contact between Burntwood group sediments and South Wekusko assemblage ocean-floor basalt, and descriptions of graphitic argillite in company drill logs, drillcore CP-10-01 was examined in detail. Narrow intervals of dark grey, thinly laminated greywacke between 107.5–125.0 m and a poorly consolidated graphitic fault zone from 155.0 to 170.0 m, typical of the Burntwood group, possibly represent structural imbricates within the monotonous dark green mafic rocks that characterize this drillcore. The upper portion of drillcore KUS303 (29.86–53.0 m) contains an intermediate rock that has a distinct spotted texture imparted by medium- to coarse-grained pyroxene phenocrysts in a fine- to medium-grained light grey groundmass. Several narrow intervals (<2 m to several metres) of felsic rocks are intercalated within the mafic rocks in drillcore KUS303, but the contact relationships are obscured by ductile deformation; these could represent dikes or structurally emplaced blocks. From 131.0 to 161.7 m laminated mafic wacke grades into felsic (chert?) fragmental rock, which has a matrix of grunerite and magnetite (Figure GS2017-7-4b), and then grades into laminated chert.

Drillcores HAR179, HAR180, HAR181, HAR254 and HAR258 (Assessment files 74565, 74942) all have relatively similar rock types, the most common being millimetre- to centimetre-scale layered mafic wacke (Figure GS2017-7-4c), which is massive in places. Each drillcore intersects a quartz-rich sulphide-mineralized interval ranging from 5 to 10 m in width (up to 40 m in drillcore HAR181); the mineralization varies from 1–5% disseminated pyrite along laminations in mafic wacke to net-textured pyrrhotite and pyrite (up to 50%) in narrow (<50 cm) stockworks associated with brecciated quartz fragments. The absence of laminations in felsic fragments suggests they are part of a quartz vein system that cuts the mineralized mafic wacke; later ductile deformation dismembered the vein and remobilized pyrrhotite into the stockworks. Intermediate to felsic feldspar-phyric dikes (<1.5 m) with chilled margins

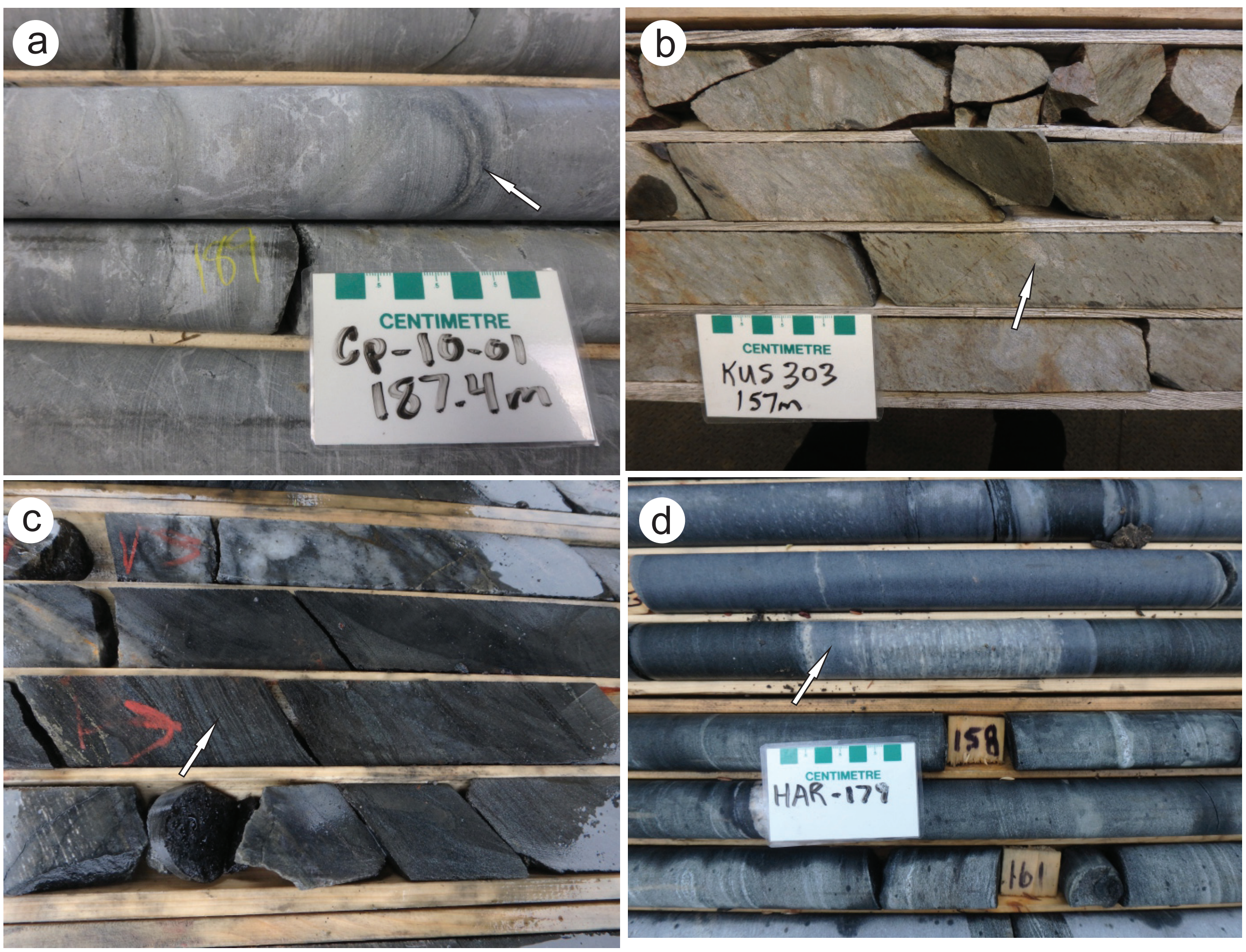


Figure GS2017-7-4: *Mafic-dominated rocks of the Clearwater domain:* ***a****) green basalt with dark green pillow selvage (arrow), drillcore CP-10-01, 187.4 m, NQ;* ***b****) grunerite-magnetite—bearing rock with felsic fragments (arrow), drillcore KUS303, 157.0 m, NQ;* ***c****) laminated mafic wacke (arrow), drillcore HAR181, 164.0 m, NQ;* ***d****) feldspar-phyric felsic dike with a chilled margin (arrow) cutting mafic wacke, drillcore HAR179, 156.4 m, NQ. Core diameter: NQ, 4.76 cm; BQ, 3.65 cm.*

commonly cut the mafic wacke (Figure GS2017-7-4d). Their absence in the mineralized mafic wacke might indicate that they predate them.

Plutonic association

Drillcores WEK-94-9 and WEK-94-10 (Assessment File 94654) both intersect homogeneous, massive, equigranular, moderately magnetic, medium-grained mesocratic gabbro (Figure GS2017-7-5a); these are similar to the gabbro in drillcores 138-27 and 138-24 (Reid and Gagné, 2016). Primary pyroxene is replaced by secondary amphibole in drillcore WEK-94-9, however, the timing and significance of this alteration is unknown. Drillcores WEK-94-13 and WEK-94-14 contain gabbro similar to that described here (see Gagné, GS2017-9, this volume for more details).

Drillcore KUS302 (Assessment File 73949) contains a complex package of rocks that varies from a greenish-black, medium- to coarse-grained amphibolite to a lighter grey, pyroxene-porphyritic intermediate rock of uncertain protolith. The intermediate rock appears to contain 1–2 cm, subangular fragments; these may be lithic fragments in a volcaniclastic precursor. However, diffuse contacts around the fragments do not allow positive identification. Intruding the above-mentioned units is a light grey, medium-grained, equigranular granodiorite (Figure GS2017-7-5b).

East Kisseynew domain

Mafic and felsic gneiss

Rocks in the East Kisseynew domain are distinctly different from rocks in the Clearwater domain in that they are heterogeneous, medium-grained, foliated to granoblastic with gneissic layering at the centimetre- to metre-scale, which is interpreted to result from pooling/segregation of leucosome derived from partial melting. These rocks vary from dark green amphibolite (mafic; Figure GS2017-7-6a) to a distinct blue-grey, quartz-feldspar-hornblende gneiss (intermediate; Figure GS2017-7-6b). Light grey to pink, medium- to coarse-grained, strongly foliated granite is intercalated with the mafic and intermediate gneiss and has a width in drillcore from a few centimetres to 35 m (Figure GS2017-7-6c). The youngest intrusive rocks are narrow granitic aplite dikes that postdate the gneissic fabric (Figure GS2017-7-6c) and may be related to pegmatite injections that formed late in the deformation history. Drillcore HAR077 (Assessment File 73949), though injected with pegmatite, does not show extensive recrystallization and contains bedded quartz-feldspar arenite that is cut by a mafic dike (Figure GS2017-7-6d). Amphibolite and quartz-feldspar arenite alternate at >10 m intervals throughout the remainder of the drillcore. The amphibolite has a layered appearance due to ubiquitous carbonate and light green amphiboles concentrated along foliation-parallel centimetre-scale seams.

East of the south Wekusko Lake study area

Drillcores HAR253, KUS356 and KUS367 (Assessment files 74844, 74705), from near the Watts River and Harmin VMS deposits to the east of the study area, are similar in that they intersect two distinct packages of rocks separated by graphite- and sulphide-bearing zones no more than a few metres wide. These zones most likely represent late faults with significant displacements, as rocks above and below show differing amounts of recrystallization and migmatization, which likely record different metamorphic histories.

Drillcore HAR253 contains grey-green, weakly layered, medium-grained, intermediate gneiss (84.7–245.4 m) that locally appears to contain flattened 2–4 cm clasts (Figure GS2017-7-7a). Minor centimetre-scale pegmatitic melt segregations occur throughout the upper portion of the drillcore; a thick interval of massive plagioclase-rich pegmatite (tonalite in composition) resides between 220.0 and 232.5 m. Fine- to medium-grained amphibolite, which has layered green to dark green domains with abundant disseminated calcite, is present

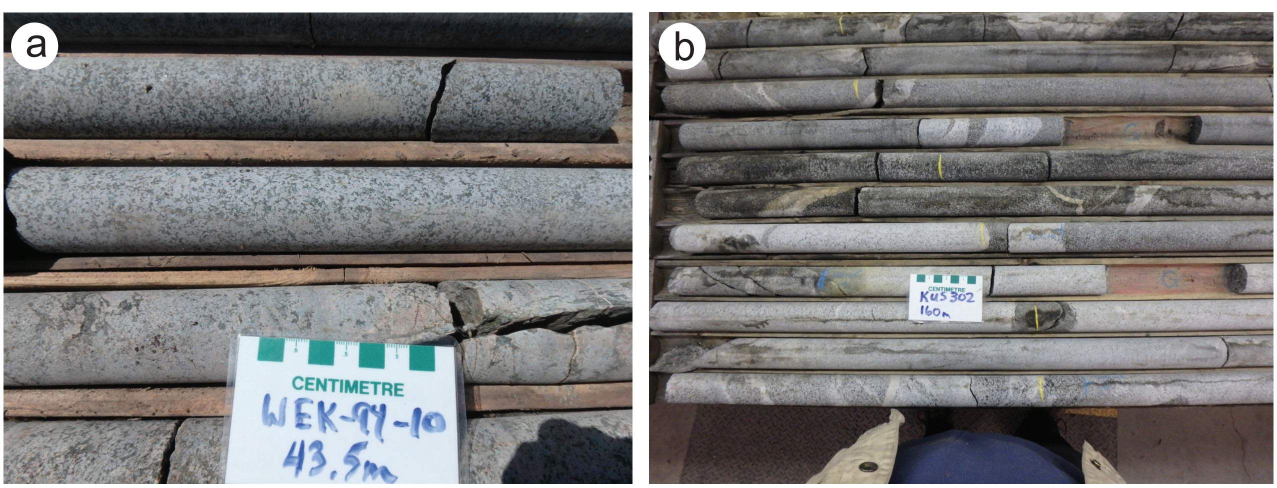


Figure GS2017-7-5: *Plutonic rocks of the Clearwater domain:* ***a)*** *medium-grained mesocratic gabbro, drillcore WEK-94-10, 43.5 m, NQ;* ***b)*** *medium-grained amphibolite intruded by granodiorite, drillcore KUS302, 160.0 m, BQ. Core diameter: NQ, 4.76 cm; BQ, 3.65 cm.*

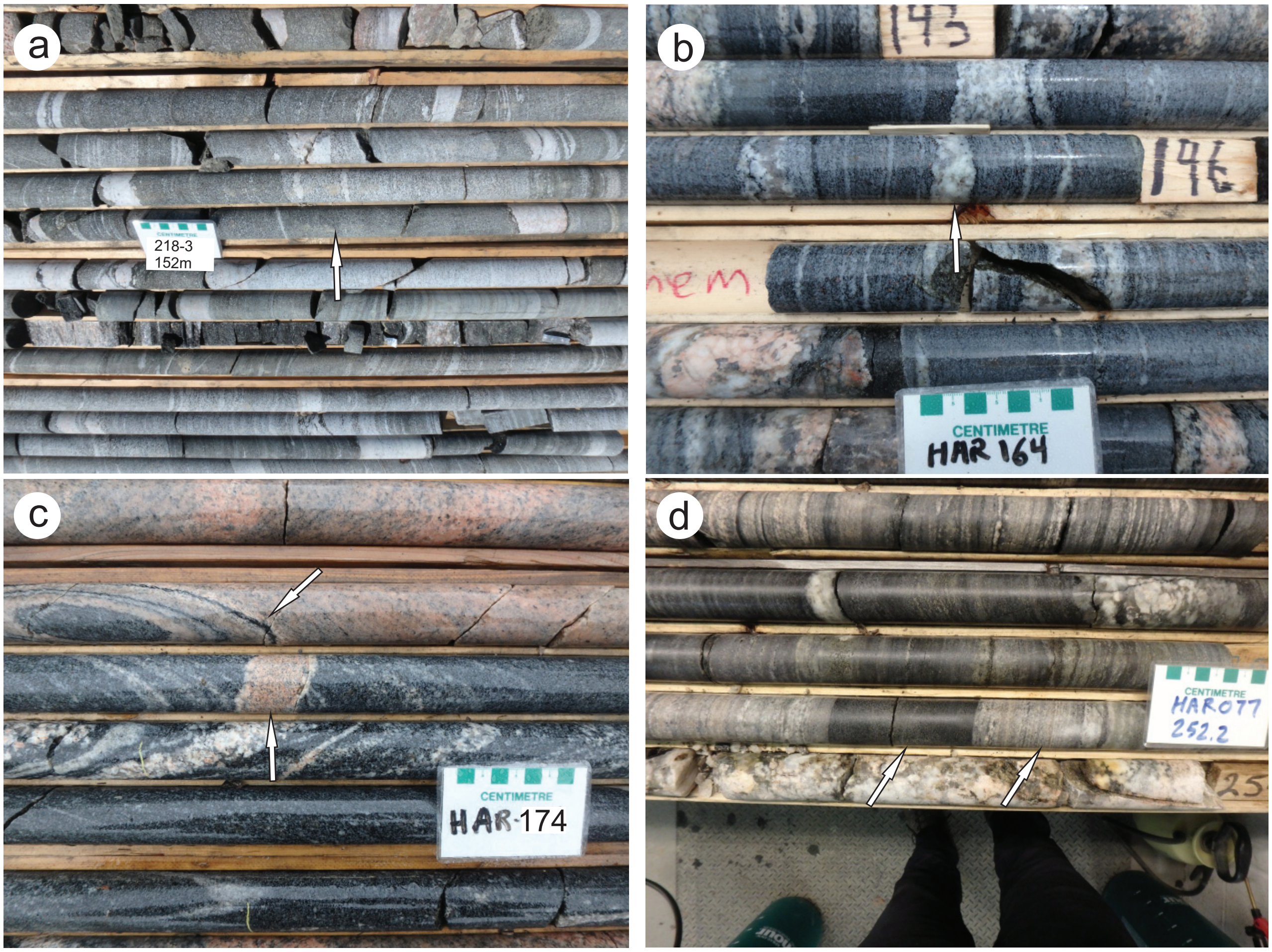


Figure GS2017-7-6: *Mafic and felsic gneiss of the East Kisseynew domain:* ***a)*** *weakly gneissic amphibolite (arrow) and granodiorite cut by pegmatitic segregations, drillcore 218-3, 152.0 m, BQ (Assessment File 71118, Manitoba Growth, Enterprise and Trade, Winnipeg);* ***b)*** *grey quartzofeldspathic gneiss with abundant migmatite sweats and biotite-rich melanosome (arrow), drillcore HAR164, 146.0 m, NQ (Assessment File 74565);* ***c)*** *gneissic amphibolite with pegmatitic injections and foliated pink granite (upper arrow); note the granitic aplite that cuts the gneissic fabric (lower arrow), drillcore HAR174, 272.0 m, NQ (Assessment File 74565);* ***d)*** *thin amphibolite dike (left arrow) in bedded quartz-feldspar arenite (right arrow), drillcore HAR077, 252.2 m, BQ. Core diameter: NQ, 4.76 cm; BQ, 3.65 cm.*

in both the lower half of HAR253 (245.4–377.0 m) and the upper section of KUS356 (49.5–189.6 m). The amphibolite in drillcore KUS356 differs in that ~5% of the unit is cut by <1 m feldspar-phyric intermediate dikes that are similar to the previously described dikes that cut mafic-dominated rocks (see 'Mafic-dominated association' section). The lower section of drillcore KUS356 (200–272 m) contains a blue-grey gneiss that is medium- to coarse-grained, layered (because of mineral segregation) and contains abundant centimetre-scale migmatite with biotite-bearing melanosome along the margins. Absence of melt-related textures in combination with the relatively fine-grained character of amphibolite in both HAR253 and KUS356 when compared to their recrystallized intermediate gneiss counterparts suggests that they evolved under differing metamorphic conditions and were tectonically juxtaposed.

Similar to the rocks described above, drillcore KUS367 contains two distinctly different packages of rocks. In the upper portion (36.1–117.7 m), intervals (1–3 m) of garnet-bearing greywacke grade into biotite-garnet±staurolite gneiss, with the contact with the next greywacke interval being sharp. The gradational nature of the two rock types followed by the abrupt truncations and is interpreted to define a series of thick beds that graded from greywacke at the base to mudstone at the top and now display reverse metamorphic grading due to enhanced recrystallization of the mudstone (Figure GS2017-7-7b). Separating the upper from the lower section is a graphite-sulphide–bearing horizon between 117.7 and 120.0 m. The lower half of the drillcore (120.0–197.0 m) includes feldspar-biotite-hornblende gneiss and hornblende amphibolite (mafic wacke protolith?), which in places contains up to 5% medium- to coarse-grained garnet porphyroblasts; contacts are gradational. The feldspar-biotite-hornblende gneiss locally contains fine wisps of a light grey, fibrous mineral, possibly sillimanite.

Drillcore KUS368 (Assessment File 74705) intersects a heterogeneous package of medium-grained feldspar-biotite-hornblende gneiss and hornblende amphibolite with two

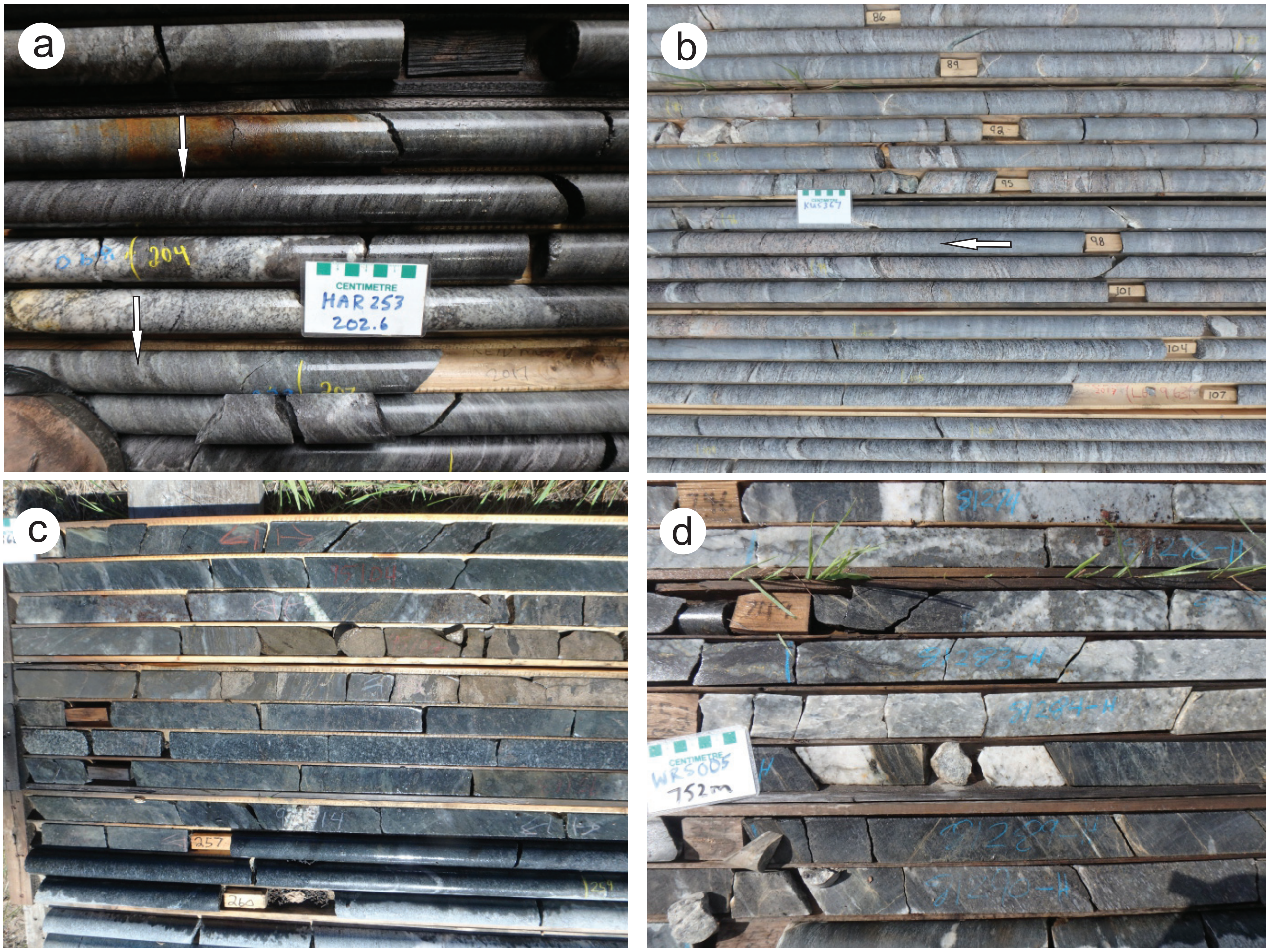


Figure GS2017-7-7: *Drillholes east of the south Wekusko Lake study area:* ***a)*** *intermediate volcanic (?) fragments (arrows) and white tonalitic pegmatite, drillcore HAR253, 202.6 m, NQ;* ***b)*** *garnet-bearing greywacke and biotite-garnet-staurolite gneiss (arrow shows direction of reverse metamorphic grading in normally graded beds), drillcore KUS367, 77–113 m, NQ;* ***c)*** *gold-bearing semi-massive pyrrhotite in intermediate gneiss, drillcore KUS368, 251.0 m, BQ;* ***d)*** *sillimanite-bearing siliceous rock beneath mineralized zone and biotite-bearing intermediate quartzofeldspathic gneiss, drillcore WRS-005, 752.0 m, BQ. Core diameter: NQ, 4.76 cm; BQ, 3.65 cm.*

sulphide-bearing zones. The first sulphide zone consists of highly tectonized pyrrhotite and pyrite, between 120 and 122 m, and is associated with light grey–green siliceous rocks that range from centimetre-scale layered rock to feldspar porphyritic rock that resembles rhyolite. The lower sulphide zone (247–251 m) is a package of semi-massive to stringer pyrrhotite that contains trace specks of chalcopyrite (GS2017-7-7c).

Drillcore WRS-005 (located at the Watts River deposit, Figure GS2017-7-2 [drillhole not shown]; Assessment File 74251) intersects copper-zinc mineralization associated with the Watts River VMS deposit (Bailes, 2015). Drillcore from 680 to 786 m was re-examined to identify the rock types that host mineralization and to select a sample for U-Pb zircon dating. Rocks from this drillcore are moderately recrystallized, medium grained and have few recognizable primary textures. However, in the structural hangingwall, from 680 to 701 m, a clast-supported felsic breccia grades downward into less recognizable intermediate quartzofeldspathic gneiss from 701.0 to 723.5 m. The contact between the relatively unaltered intermediate gneiss in the hanging wall and the mineralized zone below is sharp. The mineralized zone (723.5–734.0 m) consists of disseminated, stringer and semi-massive chalcopyrite, sphalerite, pyrrhotite and pyrite hosted by biotite±cordierite gangue. Beneath the main mineralized zone, from 734.0 to 753.0 m, is a distinctive light grey, aphanitic to fine-grained, weakly mineralized siliceous rock that contains 5–10% wisps of sillimanite (2–5 mm long; Figure GS2017-7-7d). From 753.0 to 760.0 m, the biotite content increases to ~10% and the rock contains 5–10% subrounded (1–2 cm diameter) fine aggregates of quartz and sillimanite. Downcore from 760.0 m the rock becomes an intermediate quartzofeldspathic gneiss that continues to the end of the hole (786.0 m), a sample of the relatively homogeneous intermediate quartzofeldspathic gneiss from 760.0 to 783.7 m was selected for future geochronology work.

Whole-rock geochemistry of mafic rocks

Whole-rock samples were collected by the Manitoba Geological Survey (MGS) in 2016 and analyzed at Activation

Laboratories Ltd. (Ancaster, Ontario) using lithium metaborate/tetraborate fusion for both major oxides and trace elements. HudBay Minerals Inc. collected samples from 2002 to 2012 and they were analyzed by Acme Analytical Laboratories Ltd. (now Bureau Veritas Minerals; Vancouver, British Columbia) by using a combination of lithium metaborate fusion for major oxides and digestion in a mixture of $HF:HClO_4:HNO_3$ acids for trace elements. In both cases, concentrations of analytes were measured by quadrapole inductively coupled plasma–mass spectrometry (ICP-MS). The data was imported and handled in REFLEX's ioGAS™ and subalkaline basaltic rocks were identified using the Zr/Ti versus Nb/Y diagram of Winchester and Floyd (1977; modified by Pearce, 1996); these rocks are the focus of the following descriptions. Plutonic and epiclastic sedimentary rocks were removed from the dataset. Magmatic affinity was determined using the parameters of Ross and Bédard (2009), and trace-element concentrations were plotted on spider diagrams, normalized to normal (N-type) mid-ocean–ridge basalt (N-MORB) using the values of Sun and McDonough (1989).

Rocks of basaltic composition from the bimodal volcaniclastic association in the Clearwater domain are of tholeiitic to transitional magmatic affinity (Figure-GS2017-7-8a), N-MORB–normalized trace-element diagrams have slightly concave, negatively sloped profiles with depleted Sm-Lu and well-developed negative Nb and Zr, and to a lesser extent Ti anomalies (Figure GS2017-7-8b). Heavy rare-earth elements (HREE) are relatively unfractionated, whereas the light rare-earth elements (LREE) are strongly fractionated. These features are characteristic of juvenile-arc volcanic rocks (Stern et al., 1995a; Syme et al., 1999).

Pillow basalt, massive basalt and mafic wacke from the mafic-dominated association of the Clearwater domain are mostly tholeiitic with a few samples of transitional affinity (Figure GS2017-7-8c). The N-MORB–normalized profiles are flat to slightly negatively sloped with incompatible abundances that are similar to N-MORB, with very subtle Nb, Zr and Ti anomalies (Figure GS2017-7-8d).

Based on a limited dataset, amphibolite from the East Kisseynew domain in the eastern corner of the map area and farther east (drillcores HAR077, HAR164 [Assessment File 74565], HAR253, KUS356, KUS367, KUS368) have tholeiitic to transitional magmatic affinities (Figure GS2017-7-8e, g), flat to gently negative-sloped N-MORB–normalized profiles and incompatible element abundances near that of N-MORB (Figure GS2017-7-8f, h). It is noted that these amphibolites have been affected by varying amounts of calcsilicate alteration, which may account for some variation in incompatible element contents.

Discussion

The bimodal volcanic association in the Clearwater domain shows highly variable lithology and alteration from one drillcore to the next, but some common features are apparent. Quartz-phyric dacite/rhyolite and associated volcaniclastic rocks are texturally similar in drillcores CP-11-008 (Assessment File 63J1159), 94-15 and CP-11-017, and are similar to rocks associated with VMS mineralization at the Kofman deposit (Simard et al., 2010, drillcores K08-01, K08-06, K08-07). The drillcores in this study lie along a magnetic lineament that extends southwest and northeast of the Kofman VMS deposit and possibly indicates a stratigraphic trend favourable for VMS deposits (Figure GS2017-7-2); these felsic rocks will be a focus of future geochemical investigations.

In contrast, volcanic rocks of the mafic-dominated association show less lithological variation, consisting mostly of mafic volcanic rocks, with felsic dikes and volcaniclastic rocks, chert- and silicate-facies (grunerite-magnetite) iron formation forming a volumetrically minor component. Noteworthy is a change from pillowed basalt in the west half of the mafic-dominated association (CP-10-01, KUS303) to mafic wacke/tuff in the east (HAR179, HAR180, HAR181, HAR254). Regardless of this change in facies, all basaltic samples have incompatible trace-element abundances typical of N-MORB (Figure GS2017-7-8d), though elevated Th/Nb is characteristic of basalt produced in a back-arc basin (Stern et al., 1995b).

Feldspar-biotite-hornblende gneiss, amphibolite and granite are the main rock types in the East Kisseynew domain, and have previously been interpreted as higher grade equivalents to the Burntwood group (Leclair et al., 1997). However, no aluminosilicate-bearing assemblages, typical of argillite and greywacke that has been metamorphosed to amphibolite facies, are present in the drillcores examined. Only drillcore KUS367 is interpreted to contain Burntwood group sedimentary rocks. Quartz-feldspar arenite with intercalated amphibolite (HAR077) is not common in the juvenile oceanic–arc, ocean-floor and back-arc assemblages of the Flin Flon belt. However, quartz-feldspar sandstone and conglomerate, with interleaved basalt, in the Saw Lake area are interpreted to be part of the Missi group (Bailes, 1985) and could be a lithological analogue. Of particular interest is the fact that amphibolite (of subalkaline basaltic composition) in the East Kisseynew domain that was examined has incompatible trace-element abundances typical of N-MORB and lack well-developed negative Nb, Zr and Ti anomalies characteristic of subduction-related processes. Similar to basaltic rocks in the mafic-dominated association of the Clearwater domain, elevated Th/Nb ratios may indicate that these rocks were produced in a setting that is transitional between oceanic arc and ocean floor, such as a back-arc basin (Figure GS2017-7-8f, g; e.g., Stern et al., 1995b; Syme et al., 1999).

Economic considerations

Volcanogenic massive-sulphide deposits form in active rifts in a number of geodynamic settings, including mid-ocean ridges, back-arc basins, intraoceanic arcs and continental arcs (Franklin et al., 2005; Galley et al., 2007). Geochemical studies and fieldwork have shown that most VMS deposits in the Flin Flon belt are associated with oceanic-arc volcanism, particularly during the initial stages of arc development and intra-arc rifting (Syme and Bailes, 1993; Syme et al., 1999). The geochemistry of

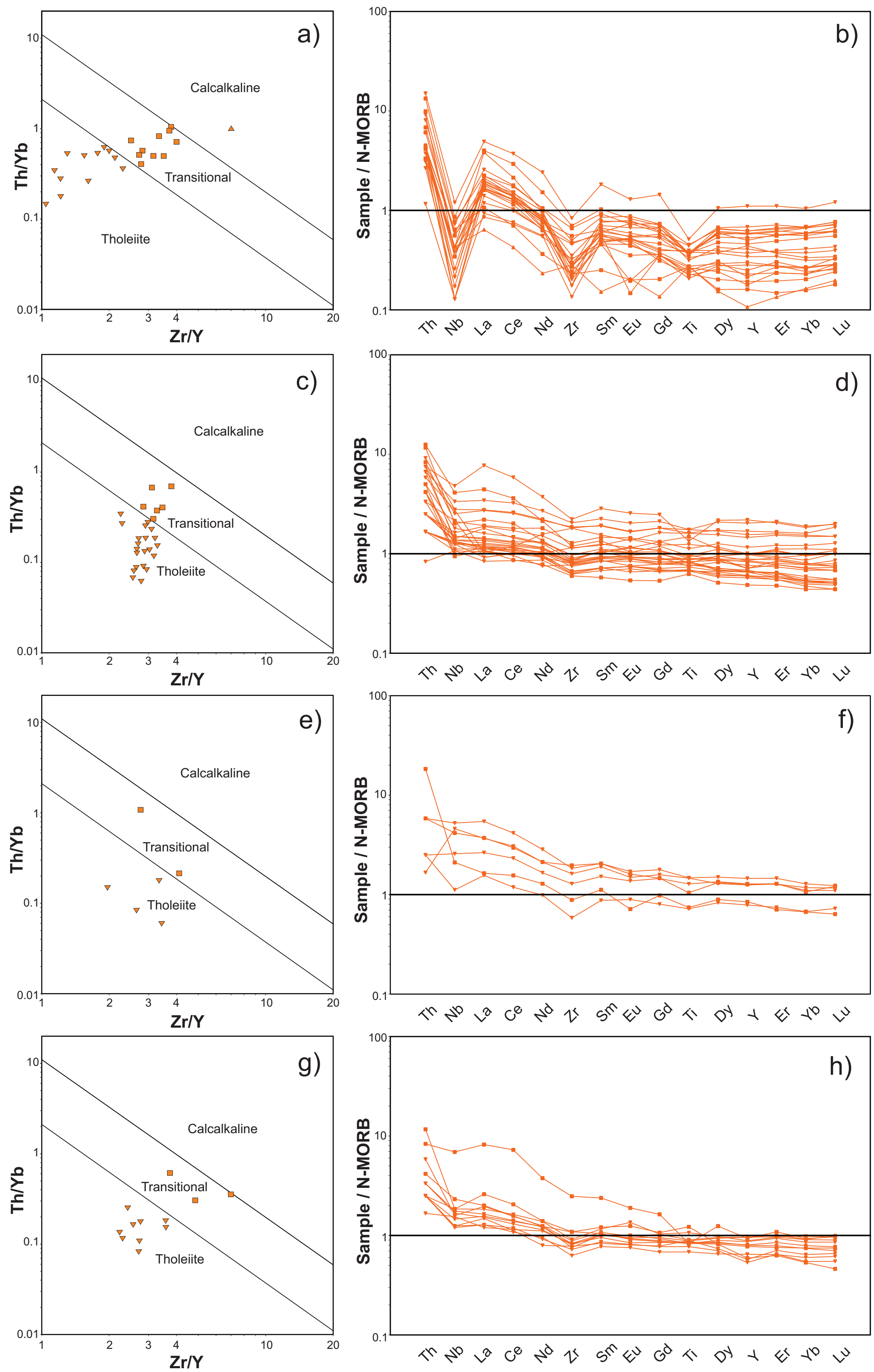


Figure GS2017-7-8: *Log Zr/Y versus log Th/Yb plots (Ross and Bédard, 2009) of magmatic affinity (down triangles, tholeitte; squares, transitional; up triangles, calcalkaline) and spider diagrams showing incompatible trace elements normalized to normal (N-type) mid-ocean–ridge basalt (N-MORB; Sun and McDonough, 1989):* ***a)*** *and* ***b)*** *bimodal volcaniclastic association in the Clearwater domain,* ***c)*** *and* ***d)*** *mafic-dominated association in the Clearwater domain,* ***e)*** *and* ***f)*** *amphibolite gneiss in the East Kisseynew domain,* ***g)*** *and* ***h)*** *amphibolite east of the study area into the East Kisseynew domain.*

rocks to the southwest of Wekusko Lake is indicative of juvenile-arc settings, suggesting above-average potential to host VMS mineralization. This is corroborated by the presence of the Copper-Man and Kofman VMS deposits (Figures GS2017-7-1, -2). Anomalous zinc and copper (2100 ppm Zn, 740 ppm Cu; Assessment File 72778) associated with quartz-phyric dacite/rhyolite, similar to that associated with the Kofman deposit, was intersected in drillhole 94-15, which is approximately 2.5 km farther to the south along strike indicating that the host stratigraphy may extend at least this far.

Of particular economic significance is the presence of feldspar-crystal tuff and associated weakly mineralized argillite/siliceous ash tuff in drillcore MUD072, with assays indicating that the latter rock type contains up to 0.08 g/t Au, 3.35 g/t Ag, 0.19% Zn, 0.05% Cu over 77.8 m (Assessment File 74711). Existing maps of the geology indicate that this drillhole is collared in plutonic rocks (Figure GS2017-7-2; NATMAP Shield Margin Project Working Group, 1998), but it is apparent that volcanic rocks are also present.

Basaltic rocks of the mafic-dominated association in the eastern Clearwater domain have trace-element signatures indicative of basalt produced in an ocean-floor or back-arc setting, and would thus be considered less prospective for VMS. However, laminated to brecciated siliceous fragments, possibly representing dismembered quartz veins, locally contain elevated gold and trace copper values (e.g., drillcore HAR181, 0.41 g/t Au from 194.0 to 195.08 m, Assessment File 74565; drillcore HAR258, 0.45 g/t Au from 167.79 to 168.49 m, Assessment File 74942; drillcore WEK-94-2, 1.56 g/t Au from 113.2 to 113.8 m [not shown on GS2017-7-2, ~1 km southeast of drillhole WEK-94-3], Assessment File 94654). Proximity to a major metamorphic gradient and crustal-scale fault (Crowduck Bay fault) suggests that this area has potential for orogenic gold mineralization. To the east, drillcore KUS368 intersects semi-massive to stringer pyrrhotite that contains significant gold values (3.58 g/t Au over 3 m, Assessment File 74705) indicating that gold-bearing fluids inundated these rocks, although the timing and style of this mineralization is not understood.

Acknowledgments

The fieldwork was made possible through the co-operation of HudBay Minerals Inc. and Royal Nickel Corporation who allowed access to their facilities to examine drillcore. The author also thanks M. Stocking, C. Stocki and S. Walker for their excellent assistance, both in the field and at the Midland Sample and Core Library. Thanks also go to C. Epp for preparing samples and thin sections, and to S. Gagné and S.D. Anderson for reviewing this manuscript.

References

Ansdell, K.M., Connors, K.A., Stern, R.A. and Lucas, S.B. 1999: Coeval sedimentation, magmatism, and fold-thrust belt development in the Trans-Hudson Orogen: geochronological evidence from the Wekusko Lake area, Manitoba, Canada; Canadian Journal of Earth Sciences, v. 36, p. 293–312.

Ansdell, K.M., Kyser, K., Stauffer, M. and Edwards, G. 1992: Age and source of detrital zircons from the Missi group: a Proterozoic molasses deposit, Trans-Hudson orogen, Canada; Canadian Journal of Earth Sciences, v. 29, p. 2583–2594.

Ansdell, K.M., Lucas, S.B., Connors, K. and Stern, R.A. 1995: Kisseynew metasedimentary gneiss belt, Trans-Hudson orogen (Canada): back-arc origin and collisional inversion; Geology, v. 23, p. 1039–1043.

Bailes, A.H. 1985: Geology of the Saw Lake area; Manitoba Energy and Mines, Manitoba Geological Survey, Geological Report GR83-2, 47 p.

Bailes, A.H. 2015: Geological setting of the Watts River base metal massive sulphide deposit; HudBay Minerals Inc., unpublished internal geological report, 70 p.

Bailes, A.H. and Galley, A.G. 2007: Geology of the Chisel–Anderson lakes area, Snow Lake, Manitoba (NTS areas 63K16SW and west half of 63SE); Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2007-1, scale 1:20 000.

Connors, K.A. and Ansdell, K.M. 1994: Revision of stratigraphy of and structural history in the Wekusko Lake area, eastern Tran-Hudson orogen; *in* Report of Activities 1994, Manitoba Energy and Mines, Minerals Division, p. 104–107.

Gagné, S. 2015: Examination of exploration drillcore from the Reed Lake area, Flin Flon belt, west-central Manitoba (parts of NTS 63K9, 10): implications for the stratigraphy of the Fourmile Island assemblage and setting of VMS deposits; *in* Report of Activities 2015, Manitoba Mineral Resources, Manitoba Geological Survey, p. 38–51.

Galley, A.G., Syme, E.C. and Bailes, A.H. 2007: Metallogeny of the Paleoproterozoic Flin Flon Belt, Manitoba and Saskatchewan; *in* Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, W.D. Goodfellow (ed.), Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 509–531.

Gilbert, H.P. and Bailes, A.H. 2005: Geology of the southern Wekusko Lake area, Manitoba (NTS 63J12NW); Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, Geoscientific Map MAP2005-2, scale 1:20 000.

Franklin, J.M., Gibson, H.L., Galley, A.G. and Jonasson, I.R. 2005: Volcanogenic massive sulfide deposits; Economic Geology, 100th year Anniversary Volume, p. 523–560.

Leclair, A.D. and Viljoen, H.J. 1997: Geology of Precambrian basement beneath Phanerozoic cover, Flin Flon Belt, Manitoba and Saskatchewan; Geological Survey of Canada, Open File 3427, scale 1:250 000.

Leclair, A.D., Lucas, S.B., Broome, H.J., Viljoen, D.W. and Weber, W. 1997: Regional mapping of Precambrian basement beneath Phanerozoic cover in southeastern Trans-Hudson Orogen, Manitoba and Saskatchewan; Canadian Journal of Earth Sciences, v. 34, p. 618–634.

Lewry, J.F. and Collerson, K.D. 1990: Trans-Hudson Orogen: extent, subdivisions, and problems; *in* The Proterozoic Trans-Hudson Orogen of North America, J.F. Lewry and M.R. Stauffer (ed.), Geological Association of Canada, Special Publication 37, p. 1–14.

NATMAP Shield Margin Project Working Group 1998: Geology, NATMAP Shield Margin Project area, Flin Flon belt, Manitoba/Saskatchewan; Geological Survey of Canada, Map 1968A, scale 1:100 000.

Pearce, J.A. 1996: A user's guide to basalt discrimination diagrams; *in* Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration, D.A. Wyman (ed.), Geological Association of Canada, Short Course Notes, v. 12, p. 79–113.

Reid, K.D. and Gagné, S. 2016: Examination of exploration drillcore from the south Wekusko Lake area, eastern Flin Flon belt, north-central Manitoba (parts of NTS 63J5, 12, 63K8, 9); *in* Report of Activities 2016, Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, p. 74–86.

Ross, P.-S. and Bédard, J.H. 2009: Magmatic affinity of modern and ancient sub-alkaline volcanic rocks determined from trace-element discriminant diagrams; Canadian Journal of Earth Sciences, v. 46, p. 823–839.

Simard, R.L., McGregor, C.R., Rayner, N. and Creaser, R.A. 2010: New geological mapping, geochemical, Sm-Nd isotopic and U-Pb data for the eastern sub-Phanerozoic Flin Flon belt, west-central Manitoba (parts of NTS 63J3-6, 11, 12, 14, 63K1-2, 7–10); *in* Report of Activities 2010, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 69–87.

Stauffer, R.A. 1984: Manikewan: an early Proterozoic ocean in central Canada: its igneous history and orogenic closure; Precambrian Research, v. 25, p. 257–281.

Stern, R.A., Syme, E.C., Bailes, A.H. and Lucas, S.B. 1995a: Paleoproterozoic (1.90–1.86 Ga) arc volcanism in the Flin Flon belt, Trans-Hudson Orogen, Canada; Contributions to Mineralogy and Petrology, v. 119, no. 2–3, p. 117–141.

Stern, R.A., Syme, E.C. and Lucas, S.B. 1995b: Geochemistry of 1.9 Ga MORB- and OIB-like basalts from the Amisk collage, Flin Flon belt, Canada: evidence for an intra-oceanic origin; Geochimica et Cosmochimica Acta, v. 59, no. 15, p. 3131–3154.

Sun, S.-s. and McDonough, W.F. 1989: Chemical and isotopic systematics of ocean basalts: implications for mantle composition and processes; *in* Magmatism in the Ocean Basins, A.D. Sauders and M.J. Norry (ed.), Geological Society, London, Special Publications, v. 42, p. 313–345.

Syme, E.C. and Bailes, A.H. 1993: Stratigraphic and tectonic setting of early Proterozoic volcanogenic massive sulfide deposits, Flin Flon, Manitoba; Economic Geology, v. 88, no. 3, p. 566–589.

Syme, E.C., Bailes, A.H. and Lucas, S.B. 1995: Geology of the Reed Lake area (parts of 63K/9 and 63K/10); *in* Report of Activities 1995, Manitoba Energy and Mines, Geological Services, p. 42–60.

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.

Whalen, J.B., Syme, E.C. and Stern, R.A. 1999: Geochemical and Nd isotopic evolution of Paleoproterozoic arc-type magmatism in the Flin Flon belt, Trans-Hudson orogeny, Canada; Canadian Journal of Earth Sciences, v. 36, p. 227–250.

Winchester, J.A. and Floyd, P.A. 1977: Geochemical discrimination of different magma series and their differentiation products using immobile elements; Chemical Geology, v. 20, p. 325–343.