GS-5 Stratigraphic and structural reappraisal of the Bidou assemblage in the vicinity of the southeastern margin of the Ross River pluton, Rice Lake belt, southeastern Manitoba, and implications for gold mineralization (part of NTS 52L14)

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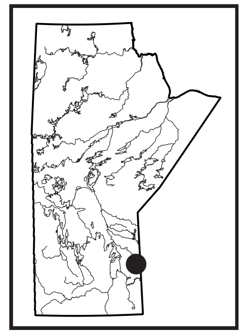

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Summary

In the summer of 2014, one month's fieldwork was carried out mainly in the vicinity of the Ogama-Rockland and Central Manitoba gold deposits, at the southeastern margin of the Ross River pluton in the southeastern Rice Lake greenstone belt. The principal objective was to refine the geological map of the area, and to better understand the lithological and structural controls on gold mineralization. A few key outcrops were revisited to document multiple stages of felsic magmatism and vein formation within the Ross River pluton. Several generations of the folds and shear zones associated with gold-bearing quartz veins were identified based on deformation styles and overprinting relationships. Vein samples from different locations along the gold-bearing vein sets were collected to constrain the absolute age of gold mineralization by means of Re-Os sulphide geochronology and U-Pb zircon geochronology.

Introduction

The late Archean Rice Lake greenstone belt is the most important lode gold belt in Manitoba, and hosts several past-producing and current-producing gold deposits. Most lode gold deposits in the belt are hosted by, or spatially associated with, brittle-ductile shear zones in greywacke, gabbro sills, basaltic flows or felsic–intermediate volcaniclastic rocks within the Neoarchean Bidou and Gem assemblages (e.g., Rice Lake mine, Central Manitoba mine); however, deposits also occur in porphyritic quartz diorite, tonalite or granodiorite of the Ross River plutonic suite (e.g., Ogama-Rockland mine). The largest deposits are concentrated along the southeastern margin (e.g., Ogama-Rockland and Central Manitoba mines) and northwestern margin (Rice Lake mine trend) of the Ross River pluton, which occupies the central portion of the belt (Figure GS-5-1).

In July 2014, fieldwork was carried out at and around the southeastern margin of the Ross River pluton, in the vicinity of the Central Manitoba and Ogama-Rockland gold deposits. This is the third field season of the first author's Ph.D. thesis project, the aim of which is to identify and interpret different generations of deformation structures associated with gold-bearing and barren vein sets. Several key outcrops were revisited to refine the accompanying preliminary geological map (Zhou, 2014), and to re-examine stratigraphic sequences, crosscutting relationships among felsic dikes and veins, and structural overprinting relationships. Geochronological samples were collected from various localities along auriferous quartz veins to constrain the timing of gold mineralization using U-Pb zircon/monazite or Re-Os sulphide dating techniques. Additionally, outcrop-scale mapping was conducted near the Rice Lake mine, northwest of the Ross River pluton, to compare the deformation structures and associated mineralized vein systems on both sides of the pluton.

This report outlines the regional geological setting and bedrock lithology of the southeastern Rice Lake belt. The different generations of folds and faults/shear zones are described based on overprinting relationships and structural characteristics, and a comparison of the vein systems within the supracrustal rocks of the Bidou assemblage and those within plutonic rocks of the Ross River pluton is made.

Regional geological setting

The northwestern Superior province in southeastern Manitoba is subdivided into three east-trending lithotectonic units based on rock type, absolute age, metamorphic grade and geophysical signature: the North Caribou terrane, Uchi subprovince and English River subprovince (Figure GS-5-1; Poulsen et al., 1996; Bailes et al., 2003; Anderson, 2008, 2013a, b). The North Caribou terrane is composed of the Mesoarchean Wallace assemblage (2.99–2.92 Ga; Davis, 1994; Percival et al., 2006a, b; Sasseville et al., 2006); Mesoarchean Garner assemblage (ca. 2.87–2.85 Ga; Davis, 1994; Anderson, 2013a, b); and English Lake, East shore and Wanipigow River plutonic complexes (3.01–2.99 Ga, 2.94–2.90 Ga and 2.75–2.69 Ga, respectively; Corfu and Stone, 1998; Whalen et al., 2003; Percival et al., 2006a, b). The interface between the North Caribou terrane and Uchi subprovince is manifested as the Wanipigow fault, which is a curvilinear, crustal-scale, subvertical shear zone with a multiphase

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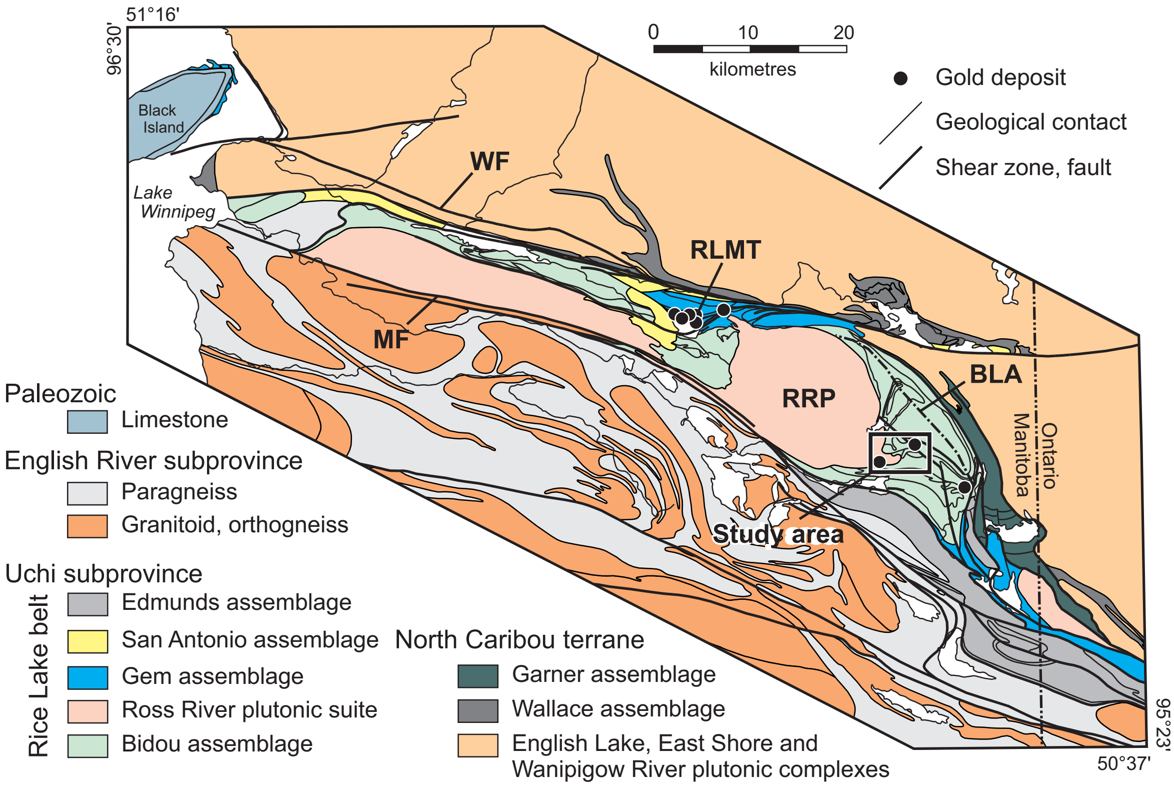

Figure GS-5-1: *Simplified regional geological map of the Rice Lake belt, showing the principal tectonic subdivisions, lithotectonic assemblages and major gold deposits. Study area is indicated by the rectangle. Abbreviations: BLA, Beresford Lake anticline; MF, Manigotagan fault; RLMT, Rice Lake mine trend; RRP, Ross River pluton; WF, Wanipigow fault. Modified from Anderson, 2013.*

deformation history (Anderson, 2008). The Uchi subprovince consists of the Neoarchean Bidou assemblage (ca. 2.75–2.73 Ga; Turek et al., 1989; Bailes et al., 2003; Percival et al., 2006a; Anderson, 2008); Ross River plutonic suite (ca. 2.73–2.72 Ga; Turek et al., 1989; Anderson, 2008); Gem assemblage (2.73–2.72 Ga; Anderson, 2013b); Edmunds assemblage (ca. 2.71–2.69 Ga; Davis, 1996; Lemkow et al., 2006; Anderson, 2013a, b); and San Antonio assemblage (<2.705 Ga; Percival et al., 2006a). The Rice Lake greenstone belt defines the western portion of the Uchi subprovince in Manitoba. The terrane boundary between the Uchi and English River subprovinces is defined by the curvilinear, crustal-scale, subvertical Manigotagan fault (Poulsen et al., 1996; Anderson, 2008). The English River subprovince is equivalent to the English River basin in Ontario proposed by Stott et al. (2010). Its constituents include medium- to high-grade metasedimentary rocks (ca. 2.72–2.7 Ga; Corfu et al., 1995; Davis, 1996; Anderson, 2013a) and voluminous diorite–tonalite–granodiorite plutonic rocks (ca. 2.7 Ga; Corfu et al., 1995), emplaced prior to the regional deformation and high-T–low-P metamorphism at 2.69 Ga (Corfu et al., 1995), which is attributed to terminal collision of the North Caribou and Winnipeg River terranes (Percival et al., 2006a, b).

Previous work

The southeastern Rice Lake greenstone belt has been extensively mapped at various scales with emphasis on sedimentation, volcanism, plutonism and/or structural geology (Stockwell and Lord, 1939; Stockwell, 1945; Campbell, 1971; Church and Wilson, 1971; Paulus and Turnock, 1971; Weber, 1971a, b; Zwanzig, 1971; Brommecker, 1991, 1996; Anderson, 2013b). Some studies are directly relevant to the lithological and structural setting of specific gold occurrences (e.g., Beresford Lake area, Brommecker, 1991, 1996; Long Lake area, Keith, 1988; Halfway Lake–Beresford Lake area, Stockwell and Lord, 1939; Ogama-Rockland mine, Troop, 1949; Garner–Gem Lake area, Anderson, 2013b). Two GAC-MAC field trip guidebooks provide comprehensive and valuable overviews of local geology, structure, lithogeochemistry, geochronology, tectonic interpretation and economic geology of the study area (Poulsen et al., 1996; Anderson, 2013a). Among these publications, Stockwell and Lord's (1939) report and three accompanying maps contain extraordinary documentation of the geology in the vicinity of past-producing mines in the Halfway Lake–Long Lake–Beresford Lake area. These authors had access to exceptionally well-exposed outcrops, which were revealed by frequent forest fires in the region, and to underground workings that have now been closed for over sixty years.

The current study was initiated in 2012 and began with camp-scale (1:1000) geological mapping near the Ogama-Rockland gold deposit. The work focused on identifying various intrusive phases, felsic dikes and quartz-carbonate veins within the southeastern margin of the Ross River pluton (Zhou et al., 2012a, b). In 2013, the map area was extended to include supracrustal rocks of the Bidou assemblage around the Central Manitoba gold deposit (Zhou et al., 2013). Detailed descriptions of map units is available in previous reports by Zhou et al. (2012b, 2013). In this report, the salient features of each map unit will be will succinctly summarized and new data, collected during field work in 2014, will be presented (Figure GS-5-2).

Bedrock units

The study area is situated in the vicinity of the south-eastern margin of the Ross River pluton. It is underlain by a variety of metavolcanic and metasedimentary supracrustal rocks of the Bidou assemblage, which are intruded by several different intrusive phases of the pluton. The Bidou assemblage is subdivided into several formations with mainly conformable depositional contacts, although they are locally reactivated as faults (Campbell, 1971; Brommecker, 1991, 1996; Anderson, 2013a). The map units identified as part of this study are largely consistent with previous subdivisions of the Bidou supracrustal rocks. The supracrustal and plutonic rocks in this district have undergone greenschist-facies metamorphism; however, primary sedimentary and volcanic structures are well preserved in most places. Therefore, we omit the

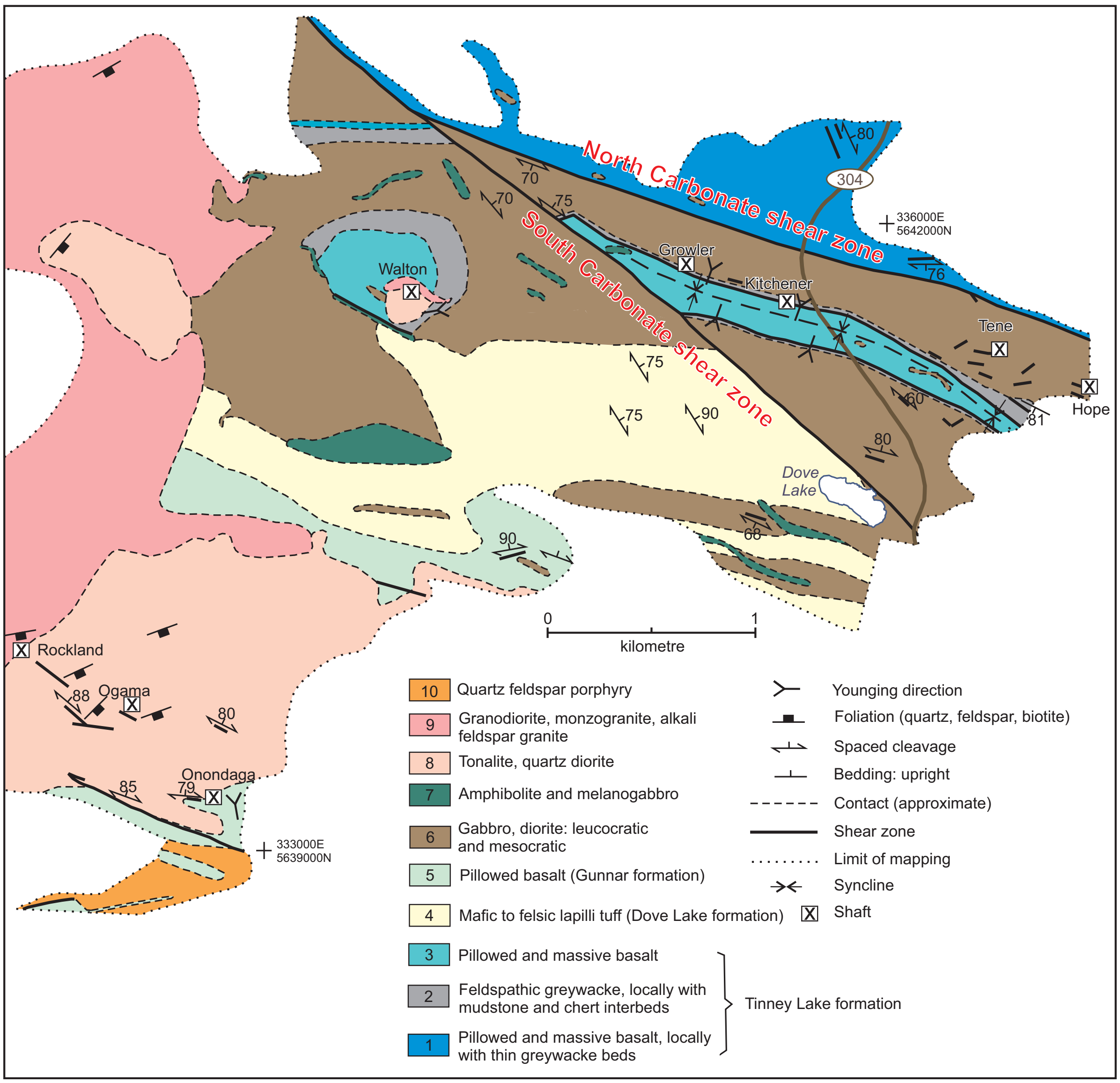

***Figure GS-5-2**: Simplified geological map of the study area near the southeastern margin of the Ross River pluton, Rice Lake belt, Manitoba, based on mapping by the first author.*

prefix ‘meta’ from our rock descriptions in the interest of brevity. Following the stratigraphic terminology of Campbell (1971), the exposed Bidou assemblage is divided into three formations within the map area: Tinney Lake, Dove Lake and Gunnar formations.

The Tinney Lake formation (units 1, 2, 3) is predominantly composed of massive and pillowed basalt, with thin normally graded beds of feldspathic greywacke, mudstone and chert. The Dove Lake formation consists mainly of mafic to felsic lapilli tuff and crystal tuff, with thin beds of intermediate tuff (unit 4). The Gunnar formation (unit 5) is composed of pillowed basalt, locally with thin beds of dacitic crystal tuff at the top. Gabbroic intrusions (unit 6) are abundant in the study area and occur as concordant sills within the volcanic and sedimentary beds, or discordant dikes that intrude supracrustal rocks. Some of the mafic dikes are amphibole-bearing (unit 7) in composition and appear to have intruded into gabbroic intrusions. The Ross River pluton intrudes both the Bidou assemblage and gabbroic intrusions, and is mainly composed of porphyritic to equigranular tonalite (unit 8) and granodiorite (unit 9), with minor quartz diorite, monzogranite and alkali feldspar granite. Quartz feldspar porphyry (unit 10) dikes with coarse phenocrysts are interpreted as comagmatic with the Ross River pluton. Late felsic dikes are abundant in the study area and intrude all earlier rocks. These dikes include quartz feldspar porphyry with fine- to medium-grained phenocrysts (unit 11), and pink and grey aplite dikes (unit 12). Aplite dikes are too thin to display on the map.

Bidou assemblage

Tinney Lake formation

The Tinney Lake formation consists predominantly of pillowed and massive basalt, with minor thin beds of feldspathic wacke, locally interlayered with mudstone and chert. Three map units (unit 1–3) are subdivided within this formation based on rock type and younging direction. It is worthwhile to note that the supracrustal rock associations east of the South Carbonate shear zone (SCSZ) are better exposed than, and slightly different in composition and texture from, western rock associations. A preliminary attempt has been made to correlate the two rock associations.

Pillowed and massive basalt, locally with thin greywacke beds (unit 1)

This unit is extensively exposed north of the North Carbonate shear zone and east of the South Carbonate shear zone. Minor outcrops are also found west of the South Carbonate shear zone. It corresponds stratigraphically to the lower to middle portion of the Tinney Lake formation (Stockwell and Lord, 1939; Campbell, 1971). The lower contact with feldspathic greywacke of the Stovel Lake formation is not exposed in the map area. Pillowed basalt in the uppermost part is separated from feldspathic wacke (unit 2) by a gabbro sill (unit 6).

Eastern rock associations consist primarily of massive basaltic flows at the bottom and pillowed basalt at the top. Massive basalt typically has black weathered and fresh surfaces. It is aphyric, with a grain size less than 1 mm. Basalt locally contains few discontinuous gabbroic dikes. Where sheared, massive basalt is strongly foliated and lineated, and locally tectonized to greenish-grey chlorite schist and mylonite. One thin ~30 cm bed of feldspathic wacke is interlayered with massive basalt. It has a light grey weathered surface and greyish-white fresh surface. It chiefly contains feldspar crystals at around 1 mm in size in a very fine grained matrix. Normally graded beds indicate younging direction is to the south. Pillowed basalt is very fine grained (<1 mm) and displays a black weathered and fresh surface. It is tens of metres thick, and varies in thickness along strike. Pillows are nonamygdaloidal and exhibit variable degrees of flattening. Primary textures such as pillow cusps suggest younging to the south.

Western rock associations are composed predominantly of black, very fined grained, aphyric massive basalt, locally with possible hornblende porphyroblasts approximately 1 mm in diameter. The massive basalt is approximately 20 m thick, and the upper contact with feldspathic wacke (unit 2) is exposed. The contact is interpreted as primary.

Interbedded feldspathic greywacke and mudstone, locally with chert and pebbly conglomerate (unit 2)

These rocks are well exposed in two thin west-trending sedimentary units consisting mainly of feldspathic greywacke, locally interlayered with mudstone to the east of the SCSZ. The northern unit (117°/80°S) is typically a few metres thick, locally up to 30 m. It has a greyish-white weathered and fresh surface. Normally graded bedding is quite common: beds range from 1 to 10 cm thick, typically with coarse-grained material at the base and gradually fining to the top (Figure GS-5-3a). Scour surfaces and flame structures occur locally but are rare. All sedimentary structures in the northern unit indicate younging to the south. The southern unit has a similar appearance to the northern; however, possible normally graded beds appear to young to the north.

West of the SCSZ, this unit occurs as an arcuate band defining a west-facing fold structure, and is probably cut by a northwest-trending shear zone that is occupied by a melagabbroic sill. Greywacke is typically interlayered with mudstone, chert and pebbly conglomerate. Normally graded beds, flame structures, crossbedding and scour surfaces are quite common in this unit. Each bed is from approximately 1 to 5 cm thick. A band of greyish-white pebbly conglomerate composed predominantly of

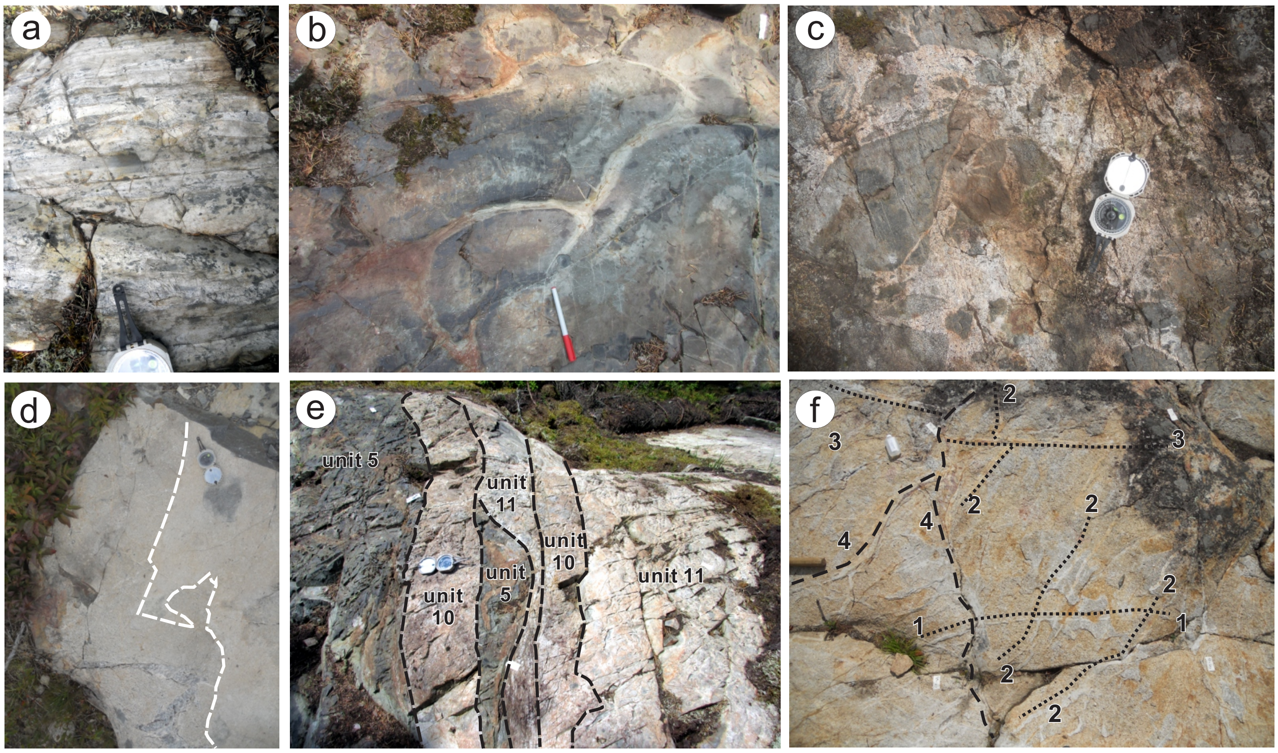

***Figure GS-5-3**: Outcrop photographs of bedrock units: **a)** thin-bedded feldspathic wacke (unit 2) close to the Growler shaft; **b)** pillowed basalt (unit 5) south of the Ross River pluton, pillow cusps and abundant radiated amygdules indicate younging direction is to the south; pen cap points north; **c)** intrusion breccia with angular xenoliths of gabbro in granodiorite in the vicinity of Walton shaft; **d)** sharp, irregular contact between coarse-grained (unit 8a) and medium-grained porphyritic tonalite (unit 8b) approximately 200 m west of the Ogama shaft; **e)** quartz feldspar porphyry (unit 10) and feldspar±quartz porphyry dikes (unit 11) intruded basalt (unit 5) near the southern contact of the Ross River pluton; **f)** different generations of aplite dikes (unit 12) within tonalite phase (unit 8a, b); see text for explanations.*

rounded feldspar-rich clasts (2–3 mm) occurs at the base. Pebble conglomerate grades to greenish coarse-grained feldspathic wacke, fine-grained wacke and mudstone. Locally a thin (~5–15 mm) layer of black chert is in contact with mudstone.

Pillowed and massive basalt (unit 3)

This unit is well exposed between two units of feldspathic wacke (unit 2) to the east of the SCSZ. It consists mainly of greenish to black pillowed and massive nonamygdaloidal basalt. Minor euhedral plagioclase phenocrysts and possibly hornblende porphyroblasts (approximately 1 mm) occur locally in massive basalt. Pillow cusps in the northern portion indicate a younging direction to the south, whereas those in the southern portion suggest younging to the north, consistent with younging criteria identified in feldspathic wacke (unit 2). A thin bed of basaltic hyaloclastite occurs close to the Kitchener vein.

West of the SCSZ, this basalt conformably overlies feldspathic wacke (unit 2) and is intruded by a small satellite stock of the Ross River pluton.

Dove Lake formation

Mafic to felsic lapilli tuff and crystal tuff, locally with intermediate volcanic beds (unit 4)

Rocks of the Dove Lake formation consist of mafic to intermediate crystal-lithic lapilli tuff with locally interbedded felsic tuff and lapilli tuff. Mafic to intermediate lapilli tuff and crystal tuff typically have greyish-green to black weathered and fresh surfaces. It is composed of 10 to 30% subrounded to subangular feldspar grains that are approximately 2 mm; from 5 to 15% irregular, angular to rounded felsic clasts, varying from 1 to 4 mm; and from 60 to 70% greyish-green to black, very fine grained matrix material. Felsic tuff and lapilli tuff, for the most part, overlie the mafic lapilli tuff. It usually weathers greyish white and has a pale white or greyish-green fresh surface. It predominantly consists of 40 to 50% subrounded to euhedral feldspar grains (1–3 mm), from 5 to 15% subrounded to irregular felsic clasts (4–8 mm), from 15 to 20% quartz and from 25 to 30% very fine grained groundmass. Felsic lapilli tuff locally contains a steep foliation defined by a preferred orientation of elongate quartz, feldspar and felsic lapilli (Zhou et al., 2013).

Gunnar formation

Pillowed basalt with radiating amygdules (unit 5)

Pillowed basalt of the Gunnar formation is abundant and well exposed in the southern part of the map area. It weathers greyish green and has a dark grey to black fresh surface. Pillows vary in size (~15–75 cm in diameter) and strain (see also Zhou et al., 2013), but commonly contain rounded to elongate yellowish-carbonate–quartz amygdules, representing radial pipe vesicles. Pillow cusps and a higher concentration of amygdules in the upper portions of individual pillows indicate this unit youngs to the south (Figure GS-5-3b). Massive basalt flows occur in the southern portion of the map area near the Onondaga shaft.

Mafic intrusions

Leucocratic and mesocratic gabbroic sills and dikes (unit 6)

This unit consists predominantly of leucocratic (mafic minerals account for less than 35 modal percentage) and mesocratic (mafic minerals account for 35–65 modal percentage) gabbroic intrusions. The gabbro typically has a spotted appearance and grain size is from approximately 2 to 4 mm. Principal minerals are plagioclase and actinolite, with subordinate blue quartz, iron-titanium oxides and carbonate. Some leucocratic gabbro includes irregular-shaped pegmatitic pods with euhedral hornblende crystals up to 1 cm in size. Based on contact relationship with country rock, some of these mafic intrusions occur as concordant sills; others appear to be discrete, discordant dikes, particularly within massive and pillowed basalt of the Tinney Lake formation. Angular gabbroic xenoliths of various sizes occur within the Ross River pluton (Figure GS-5-3c), indicating gabbro predates intrusion of Ross River pluton.

Amphibolite and melanocratic gabbroic dikes (unit 7)

This unit typically consists of discrete, curviplanar, discordant dikes, some of which appear to have followed northwest-trending, steeply dipping ductile shear zones near the Walton shaft and in the vicinity of Dove Lake. Melagabbro weathers dark grey and has a black fresh surface. It is equigranular and grain size is from approximately 4 to 6 mm. The principal minerals are euhedral amphibole (65–90%), with subordinate plagioclase, quartz, carbonate and iron-titanium oxides.

Ross River pluton

Tonalite with minor quartz diorite (unit 8)

At least three phases of tonalite are observed in the Ross River pluton: moderately foliated, coarse-grained, plagioclase-quartz-biotite–phyric tonalite (subunit 8a); moderately to strongly foliated, medium-grained, plagioclase-quartz-biotite–phyric tonalite (subunit 8b); and unfoliated medium to very coarse grained, equigranular to locally plagioclase-phyric tonalite (subunit 8c). They all have a light grey weathered surface and dark grey fresh surface. Minor amounts of moderately foliated, medium-grained, plagioclase-phyric quartz diorite are observed in the vicinity of the Rockland shaft. The northern part of the Ross River pluton contains hornblende rather than biotite as the dominant mafic mineral. It is not easy to distinguish between subunits 8a and 8b in the field; however, irregular sharp contacts are apparent in some locations (Figure GS-5-3d). Because tonalite of subunit 8b appears to cut an isolated folded quartz vein within subunit 8a tonalite, subunit 8b is interpreted to be younger. Preliminary U-Pb zircon geochronological analyses (thermal ionization mass spectrometry, TIMS) of these two deformed phases have yielded similar ages within analytical uncertainties (2728 ±1 Ma), which indicates that the difference in absolute age between these two phases is probably less than 1 m.y. Additional, more accurate and precise, geochronological results are required to verify this interpretation.

Granodiorite with minor monzogranite and alkali feldspar granite (unit 9)

Another abundant intrusive phase of the Ross River pluton is medium- to coarse-grained, plagioclase–biotite–K-feldspar–quartz-phyric to equigranular granodiorite. It is moderately foliated in the southern portion and apparently unfoliated in the northern portion. Contacts with tonalite appear to be gradational in most areas; the approximate contact is interpreted based on gradually increasing abundance of alkali feldspar. Minor isolated monzogranite and alkali feldspar granite outcrops are also observed within granodiorite.

Quartz feldspar porphyry with coarse-grained quartz and plagioclase phenocrysts (unit 10)

This unit is abundant to the south of the tonalite and intrudes pillowed basalt of the Gunnar formation. It consists primarily of euhedral plagioclase phenocrysts (10–20%) ranging from 3 to 7 mm in diameter, subhedral to anhedral quartz phenocrysts (5–10%) with a grain size of approximately 2 to 4 mm, with greyish-green very fine grained granitoid matrix (Figure GS-5-3e; see also Zhou et al., 2013). The porphyry is unfoliated at most locations. However, a weak foliation defined by a preferred orientation of tabular plagioclase crystals is present near the sheared contact between the tonalite and pillowed basalt, near the southern extent of the study area.

Felsic dikes

Quartz feldspar porphyry with fine-grained plagioclase and rare quartz phenocrysts (unit 11)

Quartz feldspar porphyry dikes, which are curvilinear and sometimes boudinaged, are abundant within the Ross River pluton and the Bidou assemblage (Figure GS-5-3e). In some locations, quartz feldspar porphyry occurs as isolated irregular bodies, easily mistaken as an enclave within tonalite. Quartz feldspar porphyry is composed of 5 to 15% euhedral plagioclase phenocrysts ranging from 1 to 3 mm in diameter and 5% or less subhedral to anhedral quartz phenocrysts, with a dark grey very fined grained or aphanitic matrix. Trace pyrite is also found in quartz feldspar porphyry dikes within the tonalite phase.

Pinkish and greyish aplite dikes (unit 12)

Aplite dikes are abundant in the map area, and intrude pillowed and massive basalt (unit 3, 5), gabbroic intrusions (unit 6) and tonalite (unit 8; see also by Zhou et al., 2013). They are usually from 1 to 10 cm thick, with over 80% fine-grained sugary feldspathic groundmass. They may or may not contain discontinuous quartz segregations or continuous smoky to pinkish quartz veins in their central portions (see also Zhou et al., 2013). Pinkish varieties typically contain less than 5% euhedral K-feldspar phenocrysts ranging from 4 to 6 mm in grain size, with less than 5 to 10% rounded quartz phenocrysts from 1 to 3 mm in diameter, and less than 5% biotite approximately 2 mm in size. Biotite content increases dramatically toward the contacts between the pinkish aplite dikes and tonalite. Trace pyrite and molybdenite flakes (~7 mm) are observed in pinkish aplite dikes. Greyish aplite dikes are typically between 1 and 10 cm thick. They usually follow ductile shear zones or occur within foliated porphyritic tonalite (unit 8a, b). Principal minerals are rounded quartz phenocrysts (5–10%), of approximately 1 to 2 mm in diameter; plagioclase phenocrysts (<5–10%), ranging from 1 to 2 mm in size; and very fine grained greyish-white feldspathic groundmass.

It is worthwhile to note that the field relationships indicate that aplite dike intrusion occurred in various stages. Complex crosscutting relationships exist between aplite dikes of distinct orientations (Figure GS-5-3f; see also Zhou et al., 2013). As illustrated in Figure GS-5-3f, a set of west-trending aplite dikes consistently cut across a north-trending aplite dike; whereas a north-trending, quartz-segregation–centred aplite dike cuts and offsets a west-trending aplite dike and is then cut by another west-trending, quartz-vein–centred aplite dike.

Pinkish aplite dikes in one location show mutual crosscutting relationships with quartz veins. A geochronological sample from the aplite dikes dated using the TIMS technique yielded preliminary U-Pb zircon dates from ca. 2724 to 2722 Ma. Three fractions of monazite from the aplite dikes yielded ages of 2732 Ma, 2725 Ma and 2714 Ma. Interpretation of these data is complicated, because the monazite contains a significant amount of common Pb. It is possible that the zircons and monazites might have inherited the Pb from adjacent plutonic rocks; therefore, the aplite emplacement may be distinctly younger than the Ross River pluton.

Structural geology

The dominant structure in the southeastern Rice Lake greenstone belt east of the Ross River pluton is an isoclinal to tight, doubly plunging anticlinorium with a northwest-trending axial planar cleavage, referred to as the Beresford Lake anticlinorium (Stockwell and Lord, 1939; Stockwell, 1945; Campbell, 1971; Brommecker, 1996). It plunges moderately to steeply to the southeast in the southeastern portion close to Beresford Lake and shallowly to the northwest in the northwestern part near Cliff Lake (Brommecker, 1996). This anticlinorium contains several large-scale tight to isoclinal folds (Stockwell and Lord, 1939; Brommecker, 1996; Anderson, 2013c).

Large-scale shear zones include the North Carbonate shear zone and South Carbonate shear zone that extend over 6 km along strike and record a complex deformation history (Stockwell and Lord, 1939; Brommecker, 1996). The North Carbonate shear zone is primarily west trending and steeply south dipping, it is a curvilinear concordant brittle-ductile shear zone situated at the contact between pillowed basalt of the Tinney Lake formation and a gabbroic sill. The South Carbonate shear zone is northwest striking and steeply northeast dipping, it is a curvilinear discordant ductile shear zone that offsets the Tinney Lake formation, Dove Lake formation, Gunnar formation and related gabbroic sills. Based on the offset contact between pillowed basalt of the Gunnar formation and felsic lapilli tuff of the Dove Lake formation, the South Carbonate shear zone exhibits an apparent dextral displacement of approximately 2 km (Stockwell and Lord, 1939).

There are abundant discrete minor brittle-ductile shear zones associated with auriferous quartz veins in the study area (e.g., Ogama shear system, Central Manitoba shear system; Figure GS-5-1). They are typically between 10 and 50 cm thick and extend tens of metres along strike. A detailed description of these systems is provided in the next section.

Several generations of deformation have been recognized because of overprinting relationships and fold styles at the mesoscopic scale. Overprinting relations among different deformation phases are consistent within the Ross River pluton and the Bidou assemblage. Correlation between deformation structures within the plutonic rocks and the supracrustal rocks is established in key outcrops at the interface between tonalite of the Ross River pluton and pillowed basalt of the Gunnar formation. Various generations of ductile deformation structures as well as brittle faults are termed G_1 to G_4, and associated folds, foliations and lineations are termed F_1 to F_4, S_1 to S_4, and L_1 to L_4, respectively.

First generation (G_1) structures

First generation deformation structures are manifested as isoclinal folds with an amplitude of approximately 10 cm within turbiditic feldspathic wacke beds (unit 2). They typically have a west-striking, steeply dipping, slaty to very closely spaced (less than 1 mm), axial planar cleavage. Fold axes plunge moderately to the west (intersection lineation L_{01} between bedding S_0 and S_1 cleavage: 274°/34°), however some of the fold axes are doubly plunging moderately to the west and to the east. In one location, a greyish-white aplite dike crosscuts F_1 folds in feldspathic wacke without discernible deformation, indicating that the folds predate aplite dikes in this location (Figure GS-5-4a).

At the macroscopic scale, the isoclinal syncline with a northwest-striking fold axial plane cleavage, south of the Kitchener shaft, also belongs to the first generation structure. In a regional context, this isoclinal syncline could be the western extension of the Beresford Lake syncline as described in the report by Stockwell and Lord (1939) and Brommecker (1991, 1996). Therefore, the double-plunging Beresford Lake anticlinorium is also interpreted as the first generation structure in the southeastern Rice Lake belt.

The S_1 cleavages are also defined by flattened pillows and varioles in basalt (unit 3; see also Zhou et al., 2013), and flattened felsic clasts in felsic lapilli tuff (unit 4; Zhou et al., 2013). Steeply plunging L_1 stretching lineations are defined by varioles in basalt as well (Figure GS-5-4b).

In the Ross River pluton, first generation deformation structures are defined by asymmetric close-folded fractures with an amplitude of half a metre, these structures are partly filled with smoky quartz veins that are commonly associated with a reddish gossan weathered surface. No associated foliation is observed with this generation of fold at the mesoscopic scale.

Second generation (G_2) structures

Second generation structures are illustrated by closed folds with an amplitude of half a metre and are found within the feldspathic wacke unit (Figure GS-5-4c). Associated penetrative axial planar cleavage, S_2, is typically spaced between 2 and 10 mm, west striking and steeply dipping. Fold axes plunge moderately to the southwest. The post-F_1 aplite dike described in the previous section also crosscuts F_2 folds in feldspathic wacke, indicating that the dike postdates two generations of folding.

In the Ross River pluton, second generation structures are manifested as tight folds with an amplitude of 5 cm and a wavelength of 30 cm. A southwest-trending, penetrative axial planar foliation (S_2) is defined by elongate biotite, quartz and plagioclase in the tonalite (unit 8a, b). The S_2 cleavage crosscuts both limbs of F_1 folds. Furthermore, the F_1 fold limb subparallel to S_2 is dramatically thinned, whereas part of the F_1 limb at high angle to S_2 is folded and thickened (Figure GS-5-4d). These observations confirm the presence of two distinct generations of folding. It is worth noting that part of the F_1 fold limb, at high angle to S_2, has variations in vein thickness as well, which implies that these variations in vein thickness partly predate F_2.

Third generation (G_3) structures

Third generation structures are visible in massive and pillowed basalt (unit 3, 5; see also Zhou et al., 2013) and tonalite (unit 8) as discrete, west- to northwest-trending, brittle-ductile shear zones that are steeply dipping and sinistral. Third generation structures also appear as west-trending sinistral slip crenulation cleavages in differentiated gabbroic intrusions (unit 6; see also Zhou et al., 2013). Kinematic interpretation is based on deflected foliation within the shear zone and offset markers (e.g., aplite dikes). North-trending, steeply dipping dextral shear zones within differentiated gabbroic intrusions are interpreted to represent a conjugate set to the west-trending sinistral shear zones. Shear zones attributed to G_3 deformation are typically free of quartz-carbonate veins. However, a north-trending, dextral shear vein and associated en échelon branches were discovered in a leucograbbroic sill and are interpreted to belong to the G_3 shear zones.

Fourth generation (G_4) structures

Although third generation and fourth generation structures are both characterized by a conjugate set of west- to northwest-trending and north- to northeast-trending shear zones, fourth generation structures are different from third generation structures in shear zone kinematics. Fourth generation structures are predominantly manifested as west- to northwest-striking, steeply dipping, dextral ductile shear zones within the Bidou assemblage and by a conjugate set of north-trending sinistral ductile shear zones and west- to northwest-trending dextral ductile shear zones within the Ross River pluton. In the Bidou assemblage, L_4 ridge-in-groove lineations occur in sheared basalt and feldspathic wacke, especially where in contact with quartz veins, and plunge moderately to the east (Figure GS-5-4e); whereas in the pluton, L_4 lineations plunge shallowly to the east or moderately to the west in ductile shear zones associated with quartz veins (Figure GS-5-4f; see also Zhou et al., 2012b). Kinematic interpretation is based on deflected foliations, shear bands and S-C fabric (Figure GS-5-4g; see also Zhou et al., 2012b). It is worthwhile to note that dominant mineralized

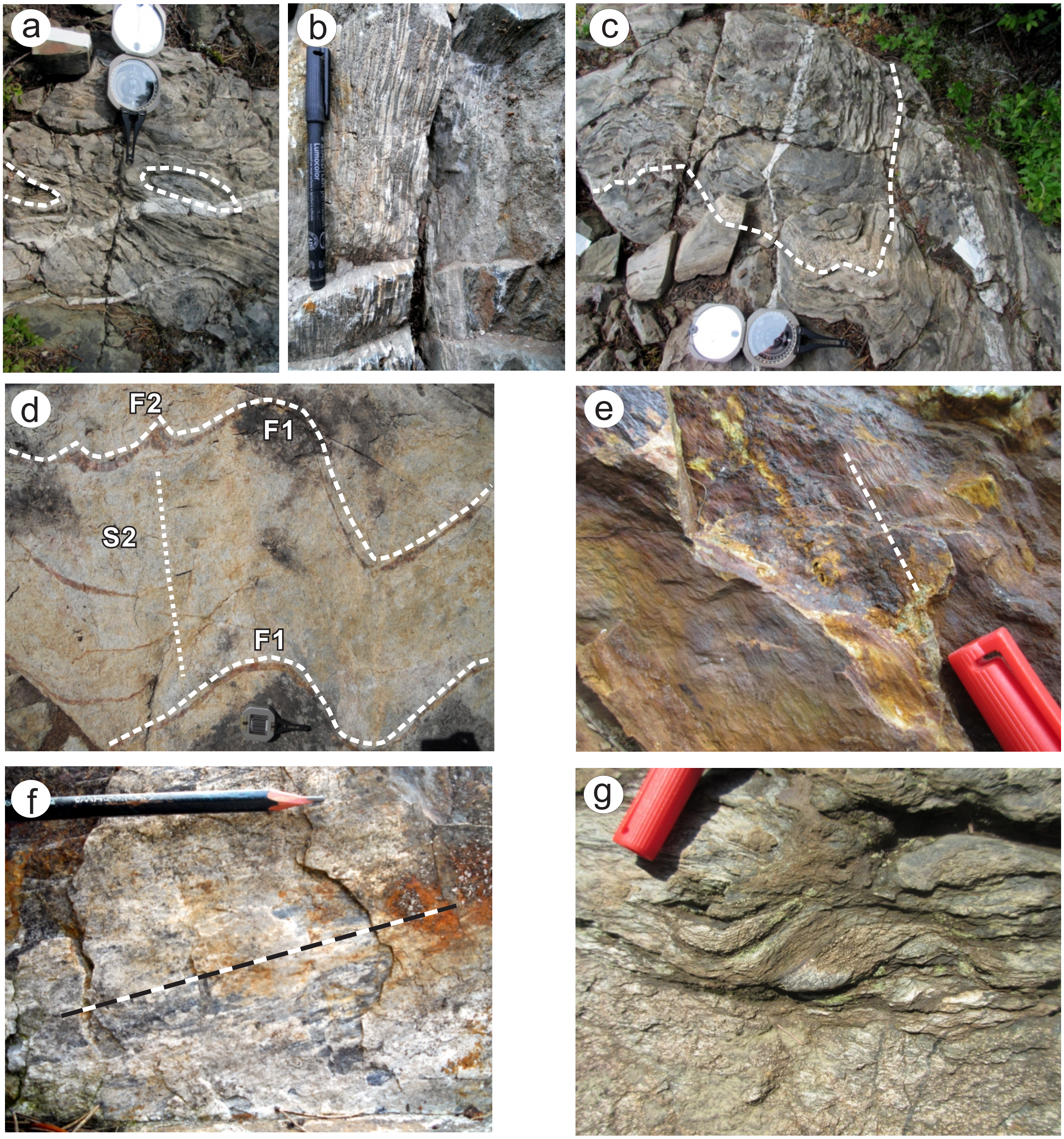

***Figure GS-5-4**: Outcrop photographs of deformation structures: **a)** isoclinal folds within turbiditic feldspathic wacke (unit 2) east of Walton shaft; compass points north; **b)** vertical view of flattened varioles in basalt (unit 3) south of Kitchener mine, looking eastward; **c)** an F_2 close fold in the turbiditic wacke (unit 2) southeast of Walton shaft; note that a greyish-white aplite dike crosscuts the folded wacke with no discernible deformation; compass points to the north; **d)** F_1 and F_2 folded veins with associated fold axial plane foliation in the tonalite (unit 8a, b), 300 m west of Ogama shaft; **e)** vertical view of ridge-in-groove slickenlines in the margin of rusty mineralized quartz vein with feldspathic wacke (unit 2), close to Kitchener mine; looking north; **f)** vertical view of ridge-in-groove slickenlines in the margin of a shear vein within tonalite (unit 8a, b), approximately 300 m west of Ogama shaft; looking southward; **g)** dextral s-type porphyroclast in sheared gabbro (unit 5), approximately 800 m west of Kitchener mine; pen points to the north.*

quartz veins are spatially associated with the fourth generation ductile shear zones.

Lode system

Ogama-Rockland gold deposit

As described in the structural section above and in reports from previous *Report of Activities* volumes, the Ogama-Rockland gold deposit is structurally controlled by a conjugate set of G_4 brittle-ductile shear zones predominantly within tonalite phases (unit 8a, b) of the Ross River pluton. Some folded veins are structurally controlled by early F_1 folded fractures and then modified by F_2 fold (Figure GS-5-4d); however, quartz veins controlled by early folded fractures are relatively rare in the map area, and it remains unclear whether or not they are auriferous. Based on crosscutting and overprinting relationships, mineralized quartz veins are divided into three sets: V_1, V_2 and V_3. The V_1 set is west-trending, steeply dipping and consists of smoky laminated sheeted quartz veinlets with trace pyrite in the tonalite (unit 8a, b) or yellowish-grey aplite dike (unit 12; Figure GS-5-5a). The laminae are defined by compositional layering of very thin foliated tonalite or aplite and thin quartz banding. No ductile shear zone is observed on the margin of quartz veins. The V_2 set consists of north-trending, steeply dipping smoky quartz veins with various orientations of brittle fractures. Slight deflection of aplite dikes and veinlets on the margin of V_2 veins suggest a shear origin. Sulphide minerals, euhedral to subhedral pyrite, anhedral chalcopyrite, minor pyrrhotite, bornite and kink-banded or crenulated molybdenite are present typically along the fractures. The V_2 set consistently crosscuts V_1 veinlets (Figure GS-5-5b). The V_3 set is mainly hosted in west-trending, steeply dipping, dextral ductile G_4 shear zones, and is interpreted to have been emplaced in the late stages of dextral shearing (Zhou

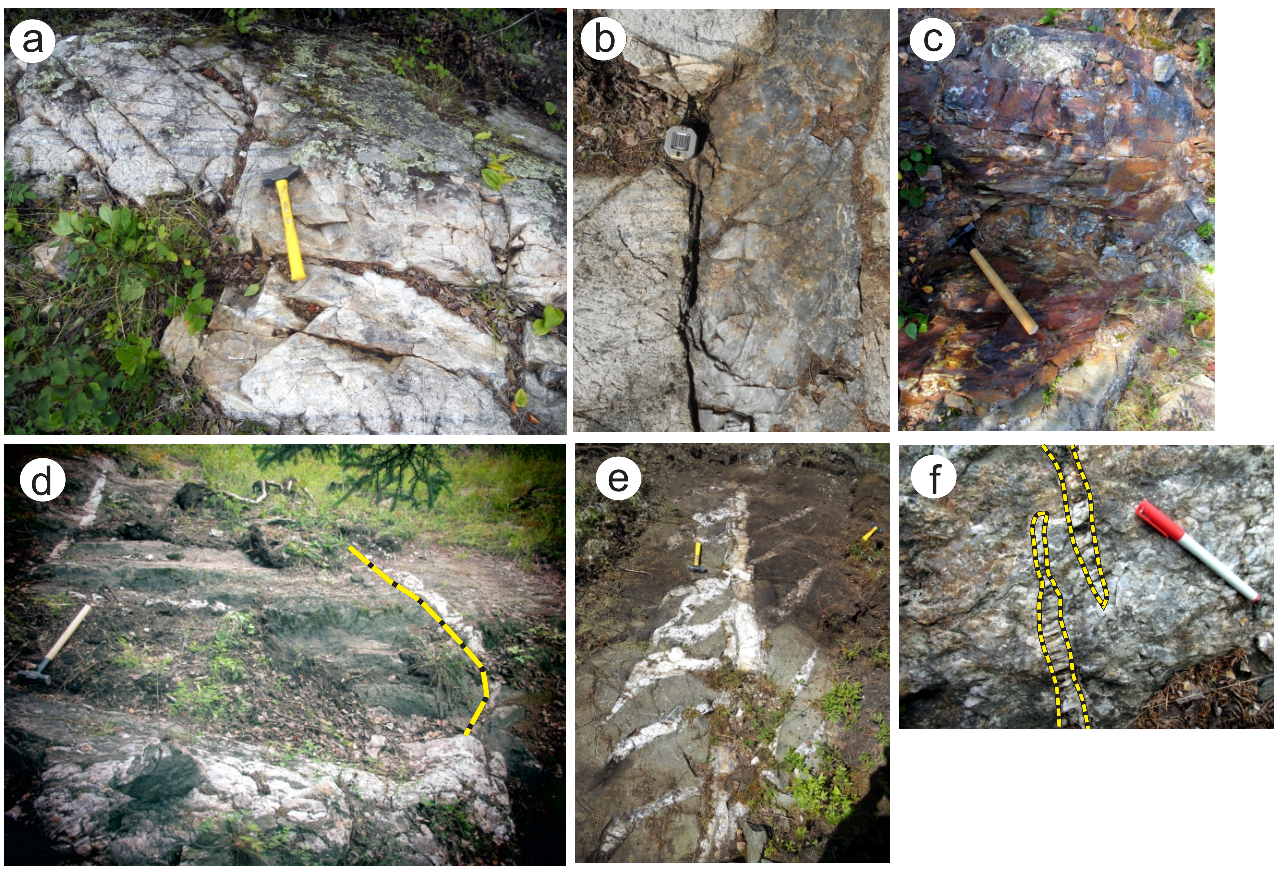

***Figure GS-5-5**: Outcrop photographs of quartz vein systems associated with the Ogama-Rockland and Central Manitoba gold deposits: **a)** west-trending, sheeted and laminated quartz veinlets in yellowish aplite dike (unit 12) and greyish-white tonalite (unit 8a, b), east of Rockland shaft; hammer is pointing to the north; **b)** a north-trending smoky quartz vein cutting across west-trending, sheeted and laminated veinlets in the tonalite (unit 8a, b), east of Rockland shaft; compass is pointing to the north; **c)** west-trending mineralized shear veins in feldspathic wacke (unit 2) close to Kitchener mine; **d)** a west-trending shear vein and north-trending extension veins in chlorite schist, south of Tene shaft; note that the north-trending vein on the right is dragged into shear zone; hammer is pointing to the south; **e)** a north-trending laminated shear vein and northeast-trending en échelon extension veins in gabbro (unit 5), approximately 200 m south of Tene shaft; looking north; **f)** two quartz veinlets with comb structure cutting across west-trending shear vein, south of Tene shaft; pen is pointing to the north.*

et al., 2012b). A set of extension veins that are spatially associated with G_4 ductile shear zones typically merge into V_3 shear veins, which are also interpreted as V_3 sets. The V_2 sets are typically displaced in a ductile or semi-brittle manner by the G_4 dextral shear zones hosting V3 veins. The typical mineral assemblage of the V_3 set consists of intact and fractured pyrite, anhedral chalcopyrite, minor bornite and visible free gold. Sericite and carbonate alteration zones are present especially along extension and shear veins associated with G_4 ductile shear zone. It is possible that these complex crosscutting vein sets (V_1, V_2, V_3) have emplaced during a progressive dextral transpressional process. A number of geochronological samples were collected from the V_2 and V_3 sets for Re-Os dating of molybdenite (and possibly pyrite) to constrain the timing of mineralization. Prior to this Re-Os dating, careful observation of ore textures is required to establish the paragenetic sequence of sulphide minerals and gold.

Central Manitoba mine trend

The Central Manitoba mine trend includes several past-producing mines, namely Growler, Central Manitoba, Kitchener, Tene and Hope. Most of these mines occur within a west-trending synclinal keel that consists of pillowed and massive basalt (unit 3), and feldspathic wacke (unit 2). A few shafts occur within gabbroic sills on the northern side of this keel. Mineralized quartz veins are lithologically controlled, occurring predominantly along the upper and lower contacts of the northern feldspathic wacke unit (Figure GS-5-5c). Minor west-trending veins are hosted by gabbroic sills. The veins are all structurally controlled by west-trending G_4 dextral ductile shear zones (Figure GS-5-5d). Chlorite and sericite±carbonate alteration is concentrated along the mineralized quartz veins, defining a zone that is typically one metre thick. Principal sulphide minerals include colloform pyrite, cubic pyrite, anhedral chalcopyrite and anhedral pyrrhotite. Minor limonite coating pyrite is interpreted as a product of supergene weathering and oxidation. Another example of vein sets is situated within gabbroic sills. The quartz vein set is manifested as a north-trending main laminated shear vein and northeast-trending en échelon extensional branches (Figure GS-5-5e). In terms of relative timing of these veins, the north-trending shear quartz veins appear to be curved into west-trending G_4 ductile shear zones (Figure GS-5-5d), whereas minor north-trending extensional veinlets with comb structure cut across the west-trending shear veins (Figure GS-5-5f). It is also possible that these complex crosscutting vein sets have formed during a progressive G_3 and G_4 deformation process. Geochronological samples of the west-trending G_4 shear veins and north-trending shear veins, and associated en échelon veins (possibly belong to G_3 ductile shearing), were collected for possible U-Pb dating of monazite or Re-Os dating of sulphide to help constrain the timing of gold mineralization.

Economic considerations

As indicated in structural geology and lode system sections, most auriferous quartz veins are structurally controlled by G_4 (minor possibly G_3) brittle-ductile shear zones within the Bidou assemblage or Ross River pluton. Aplite dikes display an intimate relationship with quartz veins within the pluton, which is evidenced by gradational transition, mutual crosscutting relationships and quartz segregations in the centre of some aplite dikes. Additional precise geochronological analyses, as well as planned fluid inclusion and isotopic analyses at the microscopic scale, combined with well-established stratigraphic and deformation sequences, will help constrain the origin of gold mineralization in the southeastern Rice Lake belt. Comparison in terms of structure and mineralization style between the northwestern and southeastern margins of the Ross River pluton may provide insight into the tectonics and metallogeny of the entire Rice Lake belt.

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