DESCRIPTIVE NOTES

INTRODUCTION

The accompanying map presents the preliminary geology of the Meadowbank gold deposit area, examined as part of the recent Woodburn mapping project of the Western Churchill Natmap program. The map is a product of 1:5 000 to 1:20 000 scale mapping on foot traverse by Wilkinson, Zaleski, and others as cited. Previous and recent studies encompassing the area include 1:5 000 to 1:100 000 scale maps of Ashton (1988), Henderson and Henderson (1994), Zaleski et al., (1997, 1999a), and Sherlock et al., (2001), and relevant reports/theses of Ashton (1981, 1982), Henderson et al., (1991), Armitage (1992 and references therein), Armitage et al., (1996), Kjarsgaard et al., (1997), Kerswill et al., (1998), Zaleski et al., (1999b, 2000) and Sherlock et al., (2001b). Early regional reconnaissance maps and reports covering parts of the area include Fraser (1988), and Schau (1983). Map compilation and interpretation by the authors also utilised archived data of Henderson (1990), the unpublished 1:20 000 scale map of Hughes and Legault (1991), and an unpublished report by Miller (1997).

The centre of the map area is situated ~80 km north of Baker Lake, Nunavut, in the Rae domain of the Canadian Shield (Fig. 1). Access is by float plane or helicopter from Baker Lake in the summer or seasonally by winter road. Bedrock exposure is moderate to poor away from lakeshore and moderate to good on the shoreline and islands of Third Portage Lake. A summary of the geologic units is presented below, along with a description of structures, metamorphism, geochemistry, and mineral potential. No stratigraphic succession is implied by the order of Archean supracrustal units in the legend. All the supracrustal rock units have been metamorphosed but for simplicity the prefix 'meta' is omitted from the legend and following descriptions. Physiographic names, including minor lakes, are informal.

GENERAL GEOLOGY

The Meadowbank deposit area is underlain by metamorphosed and polydeformed supracrustal rocks of the Woodburn group and two large domains of granitoid rocks. The Woodburn group is part of a 3000 km long Neoarchean supracrustal sequence stretching from northern Saskatchewan to Baffin Island in the Rae domain (Fig 1). The group comprises Neoarchean volcano-sedimentary rocks that have been divided into at least three distinct packages: 1) ca. 2.72–2.71 Ga ultramafic through felsic volcanic and volcaniclastic rocks with associated iron-formation; 2) quartzites, phyllites, conglomerates, and quartz-feldspar porphyry of uncertain association and 3) arkosic wackes and pelites also with interlayered iron-formation (Davis and Zaleski, 1998; Zaleski et al., 2001). Rocks of the Woodburn Lake group are polydeformed and have been overprinted by strong regional Paleoproterozoic deformation, possibly related to the Taltson-Thelon and/or Trans-Hudson orogens (Fig. 2). Pronounced transposition of some units and fold interference results in a complex map pattern with multiple repetition of units. Low pressure-high temperature metamorphism that accompanied the second regional deformation event produced a zonation from mid-greenschist to amphibolite grade, north to south, across the map area.

The Meadowbank gold deposit, which includes the Third Portage, Goose Island, Bay zone, and North Portage zone, with an estimated combined resource of 2.1 million ounces (Table 1; Cumberland Resources Ltd. press release, June 07, 2001), is dominantly hosted in oxide-silicate facies iron-formations of the 2.71 Ga volcano-sedimentary package (Zaleski et al., 1999a, 2001; Sherlock et al., 2001b). Anomalous gold occurrences were first discovered in 1983 by Wollex Exploration (a subsidiary of Comaplex Minerals Corp.). Joint venture partner Asamera further delineated the prospect through mapping and diamond drilling between 1986–91, when it was optioned by Agnico Eagle, Hecla Mining, and Lucky Eagle Mines. During the mid-1990's, partners Comaplex Minerals and Cumberland Resources Ltd. considerably expanded the known resource. Cumberland Resources, the sole owner since 1998, is presently pursuing additional gold prospects northeast of Tern Lake.

THE WOODBURN GROUP

Volcanic and related rocks

The oldest supracrustal rocks of the Meadowbank deposit area are ca. 2.71 Ga volcanic, reworked volcaniclastic and related sedimentary rocks of the Woodburn group (Davis and Zaleski, 1998). Where exposure or data are insufficient to subdivide units or facies variability occurs on too small a scale, these rocks are grouped into an undifferentiated unit, found west and southwest of Third Portage Lake (unit Awv). A dearth of facing directions and strong transposition of units precludes establishing an internal stratigraphic order within this succession.

Felsic to intermediate reworked (unit Awvc) and primary (unit Awi) volcaniclastic rocks make up the largest component of the volcanic sequence. The reworked volcaniclastic rocks are bedded to laminated wackes and tuffaceous wackes, characterized by sand to granule sized quartz eyes, subrounded to rounded plagioclase crystals, and angular to rounded, lithic clasts in a fine-grained, clastic, variably recrystallized matrix of qtz-pl-msc-chl-crb-ep. The lithic clasts comprise (in decreasing order of abundance): polycrystalline quartz (quartzite and possible vein quartz), quartz-plagioclase porphyry, bt-msc-qtz-pl schist, and rare polycrystalline pl-fs-qtz aggregates. Bedding is defined by cm- to m-scale compositional and local grain-size grading. Tuffaceous wacke typically has a greater proportion of subrounded to euhedral plagioclase crystal clasts and quartz-plagioclase porphyry clasts and a compositionally more homogeneous, well-sorted matrix. Unit Awvc is interpreted as a reworked volcaniclastic deposit owing to the presence and abundance of quartz eyes, plagioclase crystals, and quartz-plagioclase porphyry clasts, the compositional similarity between the matrix and lithic clasts, and abundance of or locally observed gradational contacts with felsic to intermediate volcanic interbeds (unit Awi).

Laminated volcaniclastic wackes with amphibole porphyroblasts (unit Awlam) are restricted to the southern part of the map area, above the amphibolite zone boundary. They are interpreted as metamorphic equivalents of unit Awvc with which they are contiguous, and can locally be difficult to distinguish from mafic intrusions where coarse, decussate amphiboles obliterate the layering.

Felsic to intermediate volcanic rocks (unit Awi) underlie the Dogleg Lake, Camp Island, and Horse Peninsula areas. Crystal and lapilli tuffs are the predominant component with subsidiary massive to layered quartz-plagioclase porphyry and probable volcanic flows. The tuffs are characterized by embayed and more rarely bipyramidal 0.5–5mm quartz crystals, broken and euhedral < 5mm plagioclase crystals, rare hornblende phenocrysts (pseudomorphed by actinolite) or dacite lapilli and crystals in a fine- to very fine-grained qtz-pl-msc ± chl or bt matrix. Rare, poorly sorted, volcanic breccias with > 25% blocks supported by an aphanitic qtz-pl-msc ± chl groundmass are noted on Horsehead Peninsula. Bedded, fine-grained tuffaceous volcanic rocks, characterised by cm- to dm-scale variations in the abundance of chlorite and muscovite and proportions of crystal clasts or lapilli, are distinguished from unit Awvc by the presence and abundance of delicate euhedral crystal clasts, lesser muscovite content, scarcity of lithic clasts, and a more homogeneous matrix. It is common for all layered or bedded units of this suite to have 2–7% disseminated and/or porphyroblastic carbonate. Occurrences of felsic volcanic rocks with up to 3% disseminated tourmaline in the matrix or minor mm-thick layers with 40% tourmaline are found throughout the unit.

Thick and continuous units of quartz-feldspar porphyry and felsic volcanic rocks (unit Awf) are differentiated in the Second Portage and Tuwawi Lake areas. These rocks are massive to layered and homogeneous, consisting of 2–5mm, euhedral quartz and plagioclase phenocrysts in an aphanitic to sugary msc-qtz-pl matrix. They have been dated at ca. 2.71 Ga (unpublished U-Pb zircon data of Davis and Sherlock) and may in part represent synvolcanic intrusions (see also Sherlock et al., 2001a, b).

Ultramafic volcanic and related rocks (unit Awkm) are present in two km-scale linear bands associated with iron-formation east of Third Portage lake, as a number of small, discontinuous horizons throughout the volcanic stratigraphy, and as generally narrow lenses at the contacts of iron-formation or quartzite. The unit consists predominantly of talc-chlorite-serpentine-magnesite, chlorite-actinolite ± magnesite or talc-tremolite-magnesite ± hornblende schists derived from variably carbonate-altered komatiitic and basaltic komatiite flows and breccia. Buff-cream dolomite-quartz-ankerite schists adjacent to the East BIF and just north of Third Portage Lake are strongly carbonated and silicified ultramafic rocks containing rare chromite, which serves to distinguish them from siliceous carbonaceous sediments. Rare primary textures include spinifex texture and polyhedral jointing. Layering on a cm- to dm-scale is defined by grain-size and compositional variations in amphibole and talc content.

Ultramafic to mafic volcaniclastic rocks (unit Awwk) generally form minor lenses within the ultramafic volcanic rocks, but particularly thick occurrences are found adjacent to quartzite at the north end of Third Portage Lake and between two quartzite panels extending from Third to Second Portage Lakes. These rocks consist of subrounded, 2–4 mm plagioclase crystals and quartz-feldspar porphyry lithic clasts in an ultramafic to mafic matrix of fine-grained chlorite and carbonate ± minor quartz or plagioclase. Rare m-scale beds with pebbles or granules of quartz-feldspar porphyry have been noted, suggesting the unit represents tuffaceous to reworked mafic-ultramafic volcaniclastic rocks.

Mafic volcanic flows and related rocks (unit Awm) typically form only minor lenses within the ultramafic rocks, but are particularly abundant along southwest Third Portage Lake, where they are associated with felsic-intermediate volcanic rocks. They are fine- to medium-grained, massive pl-act-chl schists or act-hbl amphibolites that locally display cm-scale amphibole layering. Coarser-grained flows can be difficult to distinguish from gabbros, as they have a coarsely recrystallized interstitial or relict diabasic texture. Primary structures are rare, although deformed pillows are noted on an island in southwest Third Portage Lake.

Metagabbroic rocks, including gabbro and peridotite, (unit Awa) are often associated with the mafic volcanic flows but also form mappable 250 m thick sills and several km-scale intrusions within the felsic-intermediate volcanic rocks. The gabbros are typically massive but locally have 0.5–1 cm, sub- to euhedral plagioclase phenocrysts and display a relict diabasic, ophitic or subophitic texture. The sill-like intrusions within unit Awvc have sharp contacts with adjacent host rocks and are interpreted as synvolcanic sills related to the mafic flows on the basis of a similar geochemical signature. A large composite mafic intrusion between southwest Tern Lake and Third Portage lake has a crude zonation with a central peridotite core (now serpentinite) and a gabbro/diorite rim. This unit is distinguished from unit Apgb on the basis of its plagioclase-phyric texture and geochemistry.

A variety of chemical and clastic sedimentary rocks are found as dm- to 10's m-scale beds or mappable units within the volcanic sequence. Oxide-facies, and lesser silicate or sulphide-facies banded iron-formation (unit Awif) are the most widespread, found as discontinuous thin (up to 10 m wide x 5 km long) interbeds throughout the sequence, but form thicker (10–100's m) units traceable for 10's of km at the contacts between ultramafic (unit Awkm) and felsic-intermediate volcanic or volcaniclastic rocks (units Awvc or Awms), quartz-muscovite schists (unit Awms) or quartzite (unit Aqz). The thickest units are known as the East, West, and Central BIF (Banded Iron-Formation) (Armitage et al., 1996), of which the latter hosts the Meadowbank deposit. Iron-formation characteristically contains cm- to m-scale chl ± grt-trm-cmm and qtz-msc-chl schist interbeds, interpreted as Fe-rich shales and volcanogenic wackes. Where less strained, beds in the iron-formation are defined by mm- to dm-thick, alternating quartz- or magnetite-grunerite-cummingtonite-rich bands. Sulphidic iron-formation, consisting of quartz-magnetite-pyrite-pyrrhotite ± arsenopyrite, is typically found where the iron-formation is gold-bearing.

A quartz-rich, muscovite ± chlorite schist (unit Awms) underlies much of the North Portage area and envelops the Central BIF. The schist is texturally homogeneous, fine-grained and only locally bedded, although well foliated. It contains rare 5mm polycrystalline quartz clasts, 3mm quartz eyes and trace tourmaline, kyanite and minor feldspar. Although superficially similar to foliated schists derived from unit Aqz, this unit is more compositionally heterogeneous, containing m- to 10's-m-scale layers and lenses of units Awvc and Awi. Given its relict volcaniclastic texture, interbedded volcanogenic units and K-enriched geochemical signature (Wilkinson, unpubl. data), it may represent an altered equivalent of units Awvc and Awi.

A thin but laterally continuous siliceous carbonate (unit Awsm) associated with iron-formation is present within laminated volcaniclastic wackes southeast of Third Portage Lake and felsic-intermediate volcanic rocks on Horsehead Peninsula. The marble consists of alternating cm-scale beds of fine-grained quartz dolomite, coarse dolomite, and fine- to medium-grained dolomite-calcite. The quartz-dolomite layers consist of a granular matrix of dolomite ± calcite and biotite with minor, rounded to subangular sand-size grains of quartz, and discrete lithic granules of 50% quartz-sand cemented by calcite-dolomite. The higher metamorphic grade horizon southeast of Third Portage Lake also contains tremolite, phlogopite, and rare humite. Zaleski et al., (2001) have interpreted the marble as a possible stromatolitic carbonate.

Greywacke-mudstones with minor quartz pebble conglomerate (unit Awg) underlie the northeast part of the map area. These rocks are fine- to medium-grained, well-bedded, chl-qtz-msc schists that are characterized by cm to dm-scale beds grading upward from greywacke to mudstone, and that locally display flame structures. Although the contact with adjacent reworked volcaniclastics is not directly observed, given the presence of dm-scale greywacke and conglomerate beds within unit Awvc, it may represent a more thoroughly reworked, equivalent facies of the volcaniclastic rocks.

Slate and phyllite (unit Awsl) forms several thin (< 100 m) but continuous horizons within the reworked and primary volcanic rocks. These chl-ctd ± ky bearing schists are bedded on a cm- to m-scale and are likely more prevalent than depicted, as they weather particularly recessively.

Amarulik wacke and associated rocks

A distinctive package of arkosic greywacke and related rocks, termed the Amarulik wackes (Zaleski et al., 1999a, b) occurs south of Third Portage Lake. The predominant unit is an arkosic greywacke consisting of < 3 mm quartz and feldspar crystal and lithic clasts in a coarse-grained bt-msc-qtz-fs matrix. The lithic clasts include quartzite, vein-quartz, quartz-plagioclase porphyry, and polycrystalline qtz-pl-fs aggregates. In contrast to unit Awg it is characterized by thick, dm- to m-scale, massive beds displaying only local grading, poor sorting, and more abundant feldspar crystal clasts. Oxide-facies iron-formation (unit Aaif) and pebble conglomerate (unit Aacg) are present as mappable, m- to km-scale interbeds.

The pebble conglomerate contains unsorted, granule- to cobble-sized lithic clasts in a massive quartzofeldspathic matrix. It is oligo- (quartz pebbles) to polymictic and bedded on a m-scale, containing clasts of (in decreasing order of abundance): quartzite, vein quartz, bt-msc-qtz-fs schist, and cherty oxide-facies iron-formation. Slate and siltstone (unit Aasl), as biotitic pelite, are interbedded with the thickest unit of iron-formation and underlie the eastern and western margins of the arkosic greywacke. Modified, cm-scale bedding is defined by varying proportions of biotite and compositional layers containing cordierite, staurolite, andalusite, garnet, or amphibole.

Immediately south of the map area the Amarulik arkosic greywacke forms a major regional package that is interpreted to be max. ca. 2.7 Ga (U-Pb data of Davis and Zaleski) but > 2.6 Ga (Roddick et al., 1992). In this area the Amarulik wackes also contain intermediate-mafic volcanic rocks not present in the Third Portage area, and are interpreted to be a reworked volcaniclastic deposit (Zaleski et al., 1999b). It is possible that it may be a facies equivalent of the 2.71 Ga volcanic succession.

Quartzite and associated rocks

The third major stratigraphic package of the Meadowbank map area consists largely of quartz-rich rocks; quartzites, slates and phyllites, and oligomictic to polymictic conglomerates that are considered the upper part of the Woodburn group. The quartzites themselves (unit APqz) are strongly recrystallized, massive to schistose, quartz arenites that locally contain heavy mineral layers with up to 7% magnetite-ilmenite-chromite. Primary beds (and rarely cross-beds) are noted at the cm- to m-scale, and compositional variations to more feldspathic arenite are locally noted. Minor muscovite is disseminated through the unit and defines bedforms but increases to 25% where quartzite is strongly sheared, particularly along the unit contacts and throughout the isolated quartzite body immediately north of Third Portage Lake.

Quartzite occurs as two major associations: 10's km thick units with interbedded slate and phyllite (unit APsl), such as that exposed northwest of Third Portage Lake, and thinner, up to 2 km thick, laterally continuous units intercalated with the volcanic rocks and Amarulik wackes (unit Aqz). Oligomictic quartz pebble conglomerate (units APqcg and Aqcg) is present in both associations; forming dm- to km-scale lenses interbedded with and underlying the thick quartzites and slates (as at Tuwawi Lake); and m- to 100's m-scale units at the basal contact of the thin quartzite units (above the Central BIF and along Tehek arm). The conglomerate consists of white quartzite and vein quartz clasts, with minor grey polycrystalline quartz and rare fuchsitic clasts in a micaceous quartz-rich matrix. Bedding is locally defined by grading in clast size and abundance.

Polymictic conglomerate associated with quartzite has been identified at several localities; between quartzite and the volcanic sequence on the northwest shore of Second Portage Lake, and between quartzite and the West BIF on the south part of Camp island. The occurrences are at shoreline and can be submerged depending on seasonal or other variations in water levels. The Second Portage conglomerate (unit APcg) contains pebbles, cobbles, and boulders up to 1m of (in decreasing order of abundance): white to buff quartzite and vein quartz, iron-formation, grey polycrystalline quartz, intermediate volcanic rocks, and granite. It is poorly sorted and locally transitional to oligomictic conglomerate, with which it can be bedded on a m- to 10's m-scale. The West BIF occurrence (unit Acg) is dominated by quartzite pebbles, polycrystalline quartz and iron-formation clasts, and occurs at an apparent conformable contact between Archean quartzite and ultramafic rocks.

The association of polymictic and oligomictic conglomerate with thick quartzite units has been interpreted as marking an unconformable contact with underlying 2.71 Ga volcanic rocks northwest of the map area (Zaleski et al., 2000). The lower contact of the conglomerate inlier at Tuwawi lake and the large thick quartzite body to the north with is similarly interpreted to be unconformable. The relative stratigraphic position of the thinner quartzite units is presently uncertain, however both structural (Tern Lake) and possibly conformable (Camp Island) contacts with the volcanic rocks are noted. As recent U-Pb geochronology has established that a thick quartzite-slate sequence at Whitehills Lake to south is Proterozoic (Pehrsson et al., 2002), the thick quartzites and related map units are designated as Archean or Proterozoic, whereas those quartzites apparently interbedded with the Archean volcanic rocks are interpreted as Archean.

PLUTONIC ROCKS

Plutonic rocks of both Archean and Paleoproterozoic age are interpreted to be present in the Meadowbank map area. The oldest unit associated with the plutonic rocks is the Tern Lake porphyry (unit Afp), a layered, quartz and K-feldspar-phyric porphyry dated at ca. 2.63 Ga (Davis and Zaleski, unpubl. data), situated just south of Tern Lake. The porphyry is characterized by embayed to broken blue quartz crystals, euhedral microcline (0.5–5mm, locally perthitic textured) and lesser plagioclase phenocrysts in a fine- to medium-grained, quartzofeldspathic matrix. Minor biotite and relict hornblende phenocrysts (to 2 mm) have been noted and ilmenite, chalcopyrite, pyrite, and magnetite are disseminated in the matrix.

The Tern Lake porphyry is variably sheared, typically more highly strained on its margins, and shows considerable textural and grain size variation along strike. At its southwestern end it is a strongly layered, 'tuffaceous' looking rock with 'beds' outlined on 0.5–10 cm scale by the abundance of phenocrysts (sparse to 25% or locally 50%). At its northeastern end it is a well foliated to locally mylonitic, K-feldspar and plagioclase porphyritic (5–15 mm), biotite-hornblende granodiorite (unit Afpg) with up to 15% disseminated sulphides. Fine-grained porphyry can be interlayered at the 10's m-scale with coarser-grained granite. Based on the overall texture and association with coarser-grained granitic rocks, the Tern Lake porphyry likely represents a deformed high-level, locally extrusive, subvolcanic intrusion.

Systematic mapping was not conducted in the large granitoid domains that underlie the eastern and western margins of the map area, consequently only an overview of these rocks is given here. Preliminary examination suggests that the domains are composite, with at least local subphases bearing fluorite. Further subdivision is likely possible. The predominant map unit is a pink, inequigranular to K-feldspar megacrystic (1–2 cm) monzogranite to granite (unit Agt) with biotite and/or hornblende, epidote, and magnetite in a variably recrystallized groundmass. In contrast to parts of the Tern Lake granodiorite (unit Afpg), the granite is relatively leucocratic, with typically less than 7% mafic phases, although these can be highly chloritized. It is commonly well foliated, with foliation defined by alignment of megacrysts, quartz grain-shapes, and mafic minerals. The margin of the western domain is characterized by a 100's m wide zone of intense, locally mylonitic, foliation and a sheeted zone of abundant m to 100's m wide, highly sheared intrusions in adjacent country rocks. The eastern domain is less strained overall along its margin, although highly deformed granite sheets are also present along its contact zone. A composite U-Pb age of 2612 ± 4 Ma (Roddick et al., 1992) has been obtained from both domains.

Minor granitic to syenitic stocks and dykes of suspected Paleoproterozoic age (units PNgt, PHgt) are found northwest and east of Third Portage Lake, where they intrude Woodburn group volcanic rocks and Archean granite, respectively. The Nueltin granites (unit PNgt) are coarse-grained, dark red, leucocratic and are vuggy textured locally, and have similar composition, accessory mineralogy, and geochemistry as the 1.76 Ga Nueltin granite suite (Petersen et al., in press). A prominent, subcircular magnetic anomaly within the eastern Archean granite just north of a unit PNgt dyke, may be a related body. Similar small stocks, also interpreted as Nueltin granites, are found just northwest of the map area at Pipedream Lake (Zaleski et al., 1997). A small body of leucocratic, inequigranular, biotite-garnet alkalic to syenitic granite (unit PHgt) occurs just north of Tuwawi Lake. This granite is similar in composition and texture to the ca. 1.835 Ga Paleoproterozoic Hudson granites (Petersen et al., in press), a suite that occurs as abundant dykes immediately south of the map area, and as large plutons farther south towards Baker Lake.

Late crosscutting lamprophyre dykes, interpreted to be related to minette flows of the Baker Lake group (Rainbird et al., 2001), are observed in drill core (Sherlock et al., 2001a, b) and are reported to occur in outcrop (Armitage, 1992), although they but were not noted in the present mapping.

Mafic to felsic intrusions of unknown age form two distinct suites in the map area. Gabbro, quartz leucogabbro and monzodiorite (unit APgb) form small stocks southwest and east of Tern Lake and a larger composite body south of Second Portage Lake. The latter can be difficult to distinguish from recrystallized amphibole-rich gneisses of the Woodburn group. These bodies are associated with localised magnetic anomalies, a relict ophitic texture and geochemistry distinct from unit Awa. Northwest of Pipedream Lake, a gabbro body of similar geochemistry and texture intrudes the 2.6 Ga granites (Ashton, 1988), allowing the possibility that unit APgb is Paleoproterozoic in age.

Biotite-muscovite granite is present in the map area as dykes and sheets and several minor stocks that intrude the volcanic sequence (unit APgm). These leucocratic, inequigranular to weakly K-feldspar porphyritic intrusions are characterized by 5–7% biotite and lesser muscovite in a foliated to locally mylonitic, recrystallized groundmass. They are not observed to cut the other intrusive rocks, consequently their relative age is uncertain.

STRUCTURE

Four phases of ductile deformation affect all rocks of the Woodburn group in the Meadowbank deposit area, and are correlated with structures identified regionally (Pehrsson et al., 2000). The sequence elaborated here builds on that established by Henderson et al., (1991) and Ashton (1988).

The first recognised deformation comprises outcrop- and thin section-scale evidence for two sets of pre-S_1 isoclinal folds and foliations that are found only within the 2.7 Ga Woodburn group volcanic and related rocks. These local observations and the significantly greater intensity of overall strain in this sequence suggest that the 2.7 Ga volcanic rocks were likely deformed prior to deposition of the thick quartzite sequence.

The earliest regional deformation event, D_1, involved development of macroscopic, shallowly-plunging, isoclinal folds (F_1), bedding subparallel foliation (S_1), and mineral and clast elongation lineations (L_1). S_1, axial planar to F_1 folds of bedding and quartz veins, is defined by phyllosilicate and chlorite alignment and quartz grain shape fabrics in the supracrustal rocks, and phenocryst elongation and mineral shape fabrics in all plutonic rocks with the exception of units PNgt and PHgt dykes. S_1 can be the dominant foliation observed in outcrop (S_m) but is ubiquitously folded by mesoscale F_2 folds and variably overprinted by S_2, making delineation difficult in the field. The timing of D_1 is bracketed by intrusion of the 2.59–2.62 Ga granite suite and 1.835 Ga, the age of a post-D_2 pegmatite dyke (Roddick et al., 1992; Pehrsson et al., 2000). Variable, inhomogeneous development of S_1 in the granites (cf. Ashton, 1988; Davis and Zaleski, 1998) most likely reflects regional strain heterogeneity. If S_1 schistosity in the ca. 2.0 Ga Whitehills conglomerate (Davis and Zaleski, unpubl. data) is correlative with S_1 of the deposit area the regional D_1 deformation event may also be Paleoproterozoic in age.

The predominant structures of the Meadowbank area, those related to the second phase of regional deformation (D_2), comprise tight to isoclinal folds (F_2), axial planar foliations (S_2), crenulation or intersection lineations (L_2), and reverse faults or shear zones (Fig. 4a). S_2 varies from a schistosity or differentiated to crenulation cleavage to a transposition foliation depending on host lithology and intensity of S_1 development. It locally obliterates bedding and S_1. The main regional foliation mapped in outcrop (S_m) is typically an S_1 or S_1/S_2 transposition foliation.

F_2 folds at all scales are shallowly doubly-plunging folds of S_1. North and west of Third Portage Lake they form a map-scale northwest-vergent fold set with moderately southeast-dipping axial surfaces (Fig. 4a). South of Third Portage Lake consistent S_2/S_1 asymmetry and change in S_1/S_m attitude define a regional F_2 synform, overturned to the west. North and east of Second Portage Lake F_2 axial surfaces and S_2 have variable orientations due to superposed F_4 folds (Fig. 4b,c). The regional northwest-vergent D_2 fold-fault belt deforms the Archean granites, and does not predate their intrusion as suggested by Henderson et al (1991).

A major NW-vergent D_2 thrust fault places 2.71 Ga Woodburn group volcanic rocks on the unconformably overlying quartzite sequence north of Third Portage Lake. This structure may link with a zone of D_2 high strain that extends through the deposit area and south through Second Portage Lake (Fig. 4d). This zone is characterized by increased tightness of F_2 folds, strong S_2/S_1 transposition fabrics and local mylonites, and has been termed the Third Portage fault zone by Hughes and Legault (1991). A similar zone of D_2 high strain follows the quartzite/BIF/komatiite contact at Camp Island and extends south of Third Portage Lake where a F_2 synformal fold of iron-formation is apparently truncated against its trace, suggesting the zone may be the locus of significant dislocation, and possibly a thrust fault.

The maximum age for D_2 deformation is 2.0 Ma, the maximum age of the Whitehills conglomerate (Davis and Zaleski, unpublished data), which carries the S_2 foliation. Like D_1, the lower bound for D_2 is 1835 ± 1 Ma, the age of a granite pegmatite dyke that crosscuts S_2 south of the deposit area (Roddick et al., 1992). The best estimate of the age of deformation is provided by U-Pb ages of ca. 1.8–1.9 Ga obtained from monazites within syn-D_2 staurolite porphyroblasts in rocks northwest of the map area (Berman and Pehrsson, unpubl. data). The similarity between the attitude and vergence of D_2 structures in the Woodburn group and the Amer fold-thrust belt (Patterson, 1986) has been previously noted by Ashton (1988), Davis and Zaleski (1998) and Zaleski et al., (2000).

D_3 structures consist of open to close F_3 folds of S_2/S_m with an associated L_3 crenulation lineation. F_3 chevron to similar-style folds of S_2 and L_2 have wavelengths on the order of decimetres to centimetres. The shallowly plunging to subhorizontal L_3 crenulation lineation, itself subparallel to F_3 fold axes, is locally the dominant lineation in outcrop and crenulates minerals such as grunerite that are randomly oriented on S_2. F_3 folds define a consistently southeast-verging minor fold set with shallowly north- and northwest-dipping (< 40°) axial surfaces. These folds locally overprint structures in the deposit area and can be responsible for variable S_2 dips. S_3 foliations, defined by crenulations of S_2 and new growth of muscovite or chlorite, are typically only visible in thin section.

Mapping east of Whitehills Lake (Zaleski et al., 2000) indicates that D_3 structures overprint a suite of syeno-monzodiorite intrusions that are correlated, on the basis of composition and geochemistry, with dated, ca. 1835 Ma intrusions at MacQuoid Lake (Davis, unpublished data). This suggests that D_3 deformation postdates ca. 1840 Ma. A lower bound is provided by a ca. 1790 Ma Ar-Ar age on M_3 porphyroblastic biotite that is crenulated by S_4. Zaleski et al., (1999) have previously drawn attention to the nearly identical orientation, geometry and vergence of F_3 folds and D_2 structures in the Amer group.

D_1 through D_3 structures are folded about a map-scale, south-plunging F_4 antiform-synform pair, centred on the North Portage area (Fig. 1). Mesoscale D4 structures include upright, open to tight F_4 folds, local steep S_4 crenulation cleavage, and related L_4 crenulation lineation. F_4 folds are moderately to shallowly-plunging, with north-northeast trending, steeply dipping (> 60°) axial surfaces (Fig. 4c). Grunerite, amphibole and biotite porphyroblasts, which overgrow S_2, are locally crenulated or wrapped by S_4 and define the spaced L_4 crenulation lineation. Local quartz-carbonate veins that occur along the axial surface of F_4 folds have chloritic alteration haloes and new growth of amphibole on vein walls and S_4 cleavage.

The deposit area is dominated by type-2, mushroom fold interference patterns resulting from superposition of upright F_4 folds on inclined, tight F_2 folds. This is best expressed by the refolding pattern of the Central and East BIF's but is also noted in outcrop-scale fold interference patterns in unit Awms. Northeast-trending, southeast-dipping F_2 folds on the west limb of the major F_4 synform progressively change attitude to south-southeast-trending and southwest-dipping on the east limb. F_4 folds in the North Portage zone plunge moderately south and southwest, down the dip of F_2 limbs. In contrast, F_4 folds at the Bay zone to the south locally plunge moderately to steeply northeast, due to interference with northeast-dipping limbs of tight F_2 folds. D_4 deformation of the Meadowbank deposit area appears to only remobilize pre-existing mineralization, however, it may have facilitated mineability or exposure of the deposit due to the geometry of fold interference. The established $D_2/D_3/D_4$ succession and overprinting are consistent for the area from north Third Portage Lake to Goose and Camp Islands. Further south local outcrop evidence suggests a D_5 phase of deformation or the possibility that D_4 deformation was continuous with D_3.

The absolute upper limit on the age of D_4 deformation is ca. 1840 Ma, the age of the monzodiorite intrusive suite that is overprinted by D_3/D_4 interference folding in the Tehek Lake area (see also Zaleski et al., 2000). As noted above, biotite porphyroblasts with Ar-Ar ages of ca. 1790 Ma are crenulated by S_4. Depending on the regional cooling history of the area (a subject of continuing study), this could provide the maximum age of D_4. The absolute minimum age is thought to be ca. 1760 Ma, the age of the MacRae diabase dykes (Lecheminant, pers. comm.), however this type of deformation is unknown in the Baker Lake Group (Fig. 2).

METAMORPHISM

The map area preserves evidence of three distinct metamorphic events, designated M1 to M3. M1 regional metamorphism is outlined by low to mid-greenschist facies mineral assemblages that define S_1 fabrics. It occurred at unknown pressure and is constrained to predate development of D_2 structures ca. 1.8–1.9 Ga and post-date the 2.60 Ga granites that carry S_1 foliations (Fig. 2). As is the case with S_1, M1 may post-date deposition of the Paleoproterozoic Whitehills conglomerate if regional correlation of fabrics is established.

M2 regional metamorphism is characterized by mid-greenschist through amphibolite facies assemblages (summarised in Table 2) that are interpreted to be broadly coeval with D_2 deformation, ca. 1.8–1.9 Ga (Fig. 2; Berman, unpubl. data). Greenschist zone M2 phases such as chloritoid, kyanite, chlorite, and biotite are typically aligned in or wrapped by S_2, whereas amphibolite zone porphyroblasts, including staurolite, andalusite and garnet, both overgrow and are wrapped by S_2. Local carbonate and plagioclase porphyroblasts in units Awi and Awvc display curvilinear inclusion trails smoothly continuous with matrix S_2. This evidence and recrystallization of S_1 phyllosilicates that are crenulated by S_2 suggest that M2 regional metamorphism was broadly coeval with D_2 but that the thermal peak outlasted regional deformation.

Distribution of characteristic mineral assemblages defines three metamorphic mineral zones: mid-greenschist, upper greenschist or epidote amphibolite, and amphibolite (Fig. 5). The mid/upper-greenschist zone boundary trends southeast from Tuwawi Lake, across Third Portage Lake and east-northeast just north of the Third Portage deposit. The upper-greenschist/amphibolite zone boundary trends roughly east-west across Third Portage Lake, passing just north of Goose Island. The presence of kyanite after pyrophyllite in quartzite or phyllite and grunerite-chlorite in iron-formation constrain P-T conditions of the M2 mid-greenschist zone to ca. 400°C at min. 2.7 kbar. Assemblages of the upper-greenschist zone collectively suggest temperatures of ca. 450°C at low pressures. The occurrence of the assemblage bt-st-and-musc at ~120 m depth in drill core (L'Heureux, unpub. data) and quantitative thermobarometric data (Miller, unpub. report) yield amphibolite zone conditions of 3.0 kbar at ca. 549°C, for Goose Island, just south of the zone boundary. Local fo-tlc ± tr assemblages in ultramafic rocks and the maximum stability range of chloritoid-kyanite (also ca. 550°C) are consistent with these estimates. South of Third Portage Lake, humite in phlogopite marble suggests M2 temperatures locally attained 600–650°C. The trace of the upper-greenschist and amphibolite zone boundaries crosscut D_2 structural trends, possibly due to post-thickening thermal relaxation.

M3 metamorphism is defined by new growth of mineral phases that everywhere overgrow S_2 and locally S_3 fabrics, but are wrapped and/or crenulated by S_4. These phases, characteristically porphyroblastic bt, grt and cum or act, are patchily distributed across the mid-upper greenschist and amphibolite zone boundaries (Fig. 5). South of Third Portage Lake, distinct late chlorite and muscovite are widespread and similarly crenulated by S_4. Pressure-temperature estimates of ca. 450°C at 3.0 kbar have been obtained from M3 grt-chl and grt-bio assemblages in drill core at the Third Portage deposit (Armitage, 1992). Ar-Ar (Villeneuve and Kjarsgaard, unpub. data) and K-Ar (Armitage et al., 1996) ages of M3 biotite porphyroblasts in the deposit area are 1790 ± 12 and 1791 ± 32 Ma, respectively, indicating the time of cooling through the 300°C isotherm. It is possible that M3 metamorphism represents a local, thermal aureole effect related to Nueltin suite magmatism.

ECONOMIC GEOLOGY

The Meadowbank gold deposit comprises four deposit zones localised within and adjacent to iron-formation of the Central BIF (Fig. 4d). Gold occurs in iron-formation at its contact with komatiite or volcaniclastic sediments and only in those iron-formations associated with the ultramafic/volcaniclastic interface, small units within the volcaniclastics entirely or within the Amarulik wackes are uneconomic to barren. The deposits are concentrated in the noses and along the limbs of D_1 and D_2 isoclinal folds, and show multiple styles of sulfide mineralization (Pehrsson et al., 2000, Sherlock et al., 2000a, b), associated to varying degrees with prospective gold concentrations. These styles are grouped according to their relationship to the major deformation phases, pre-syn D_2, syn-D_2 and post-D_4.

Pre- to syn-D_2 mineralization most commonly comprises pyrrhotite, locally pyrite and rarely arsenopyrite and variable gold concentrated within S_1 and S_2 foliations, with or without magnetite. These sulphides are also found within or adjacent to quartz veins deformed in S_1 or S_2 foliations and veins that cut S_1 but are deformed by D_2 (Pehrsson et al., 2000). Quartz-epidote-sulphide veins from outside the deposits themselves define F_1/F_2 interference patterns at thin-section scale and are localised along shears parallel to S_2. Regional evidence for pre D_1 mineralization comes from disseminated pyrrhotite and chalcopyrite in units Awms, Awf and Awi that display grain shape fabrics elongate in S_1, and from graded pyrrhotite concentrations in volcaniclastic rocks at Goose Island. The latter texture was interpreted by Miller (1997) to represent syngenetic-mineralization. Pre-S_1/S_2 quartz-feldspar porphyry dykes in drill core at the deposit are associated with minor Cu-Au-Ag mineralization as are parts of unit Afpg (Kerswill et al., 1998), which is dated at ca. 2.63 Ga (Davis and Zaleski, unpublished data).

Syn-D_2 mineralization comprises secondary sulfides (pyrrhotite ± pyrite) and gold that occur in S_2 parallel ductile-brittle shears at the iron-formation-komatiite contact and internal to the iron-formation, and within patchy zones that cut earlier sulfide and magnetite layers in S_1 or S_2 (Pehrsson et al., 2000). The shears may be genetically related to the D_2 strain zone that follows the komatiite-bif and quartzite contact through the deposit area (Fig. 4d). The patchy textured sulphides are locally associated with in-situ brecciation, quartz veins and silicification in D_2 dilatant zones.

Regionally, minor pyrrhotite, ± pyrite and arsenopyrite are present as blebs and streaks along S_2 crenulation cleavages associated with mesoscale F_2 folds in the iron-formation and units Awms and Awvc. Minor syn-D_2 quartz-carbonate veins are present throughout the map area. These veins show two subsets; earlier veins that folded by F_2 folds but locally cut S_2, and later veins that are parallel to F_2 axial surfaces. In the komatiitic rocks they are associated with syn-M_2 coarsening of fe-chlorites, fluid infiltration, and carbonitization whereas in units Awvc, Awf and Awi they are associated with concentration/remobilization of pyrrhotite/pyrite and ilmenite/magnetite and coarsening of amphiboles. Quartz-carbonate-epidote ± allanite veins and carbonate-epidote-chlorite vienlets that are parallel to S_2/S_1 and crosscut S_1/S_m are associated with epidote and sericite alteration and concentration of pyrite that overgrows earlier deformed sulphides.

Syn-D_4 mineralization comprises coarse pyrite ± pyrrhotite are associated with quartz-carbonate veins parallel to the axial planes of minor F_4 folds and S_4 crenulation cleavages. These veins show distinct chloritic haloes and are only gold-rich where they cross the Meadowbank deposits and are barren where S_1 and S_2 foliations are gold-poor (Pehrsson et al., 2000). Remobilization of pre-D_4 sulphides parallel to S_4 is visible in thin section. Together these observations indicate that the veins and associated fluids did not introduce new sulphides or gold.

DISCUSSION

Stratigraphy and Structural Geometry

Any analysis of the structural evolution of the map area cannot be finalised without a more complete understanding of the stratigraphic relationships between the various successions. Whereas it appears that the Neoarchean volcanic and volcaniclastic rocks and thin quartzite units are likely part of a conformable stratigraphic succession, the thick quartzite-conglomerate-slate package north of Third Portage Lake is clearly deposited unconformably on the volcanic-dominated succession. This upper quartzite-dominated package is interpreted to be dated at 2.63 Ga, part of a sequence deposited unconformably on the 2.71 Ga komatiites, felsic-intermediate and related rocks of the Woodburn group (Zaleski et al., 2001). Pehrsson et al., (2002) have alternatively interpreted this as a maximum detrital age, and consider that this thick upper sequence could be Proterozoic in age, similar to the dated sequence at Whitehills Lake. Repetition of the quartzite as thinner units within the volcanic package and underlying the Amarulik wacke has been ascribed to structural interleaving by both folding and faulting (Ashton, 1988; Hughes and Legault, 1991; Henderson et al., 1991), although Ashton (1988) allowed that some quartzites could be part of the 2.71 stratigraphic package itself, an interpretation supported by Sherlock et al., (2000a, b). The Amarulik wackes themselves have previously been interpreted as volcanogenic rocks derived from and in part contemporaneous with the 2.71 volcanic sequence (Henderson and Henderson, 1994). Resolution of these stratigraphic questions awaits more detailed study.

Mineralization

Several models have been proposed for the genesis of the Meadowbank gold deposit. Miller (1997) emphasized the syngenetic nature of the sulphides for the Goose Island deposit. Armitage et al., (1996) suggested that gold mineralization was syn- to post-the 2.6 Ga granites and related to sulphidation-alteration reactions concentrated in the Central BIF during Proterozoic reactivation of Archean structures or imposition of new Proterozoic structures. Sherlock et al., (2001a, b) elaborated on this model, linking mineralization and alteration to progressive D_2/D_1 deformation and localisation of strain adjacent to the Central BIF ultramafic/iron-formation contact.

Data from this study suggests that the mineralization in the Central BIF is pre- to syn-D_2, largely ca. 1.8–1.9 Ga in age, consistent with the general models of Armitage and Sherlock. Given the evidence for high strain along the West BIF/komatiite/quartzite contact, additional influences are required to explain the localisation of economic mineralization in the Central BIF.

Inspection of the distribution of lithologies in the map area shows that unit Awms is spatially associated with the auriferous Central BIF and the Dogleg Lake synvolcanic porphyry (unit Awf), dated at ca. 2.7 Ga (Davis and Sherlock, unpublished data). Geochemical and textural evidence suggests that unit Awms is a sericite and chlorite altered rock of volcaniclastic unit Awvc protolith that was altered prior to D_1 deformation. Given this association and the local presence of anomalous tourmaline concentrations and pyrrhotite-pyrite in the unit Awf porphyry, we suggest that the distinct mineralogy of the Central BIF and distribution of the unit Awms schist may in part reflect syngenetic semi-regional alteration adjacent to 2.7 Ga porphyry. This alteration may have acted as a ground preparation event, making the Central BIF a preferential site for syn-D_2 mineralization over the West or East BIFs.

ACKNOWLEDGEMENTS

Cumberland Resources Ltd. is gratefully acknowledged for logistical support of the project, access to drill core samples and airborne geophysical data. Mike Thomas is thanked for producing vertical derivative magnetic maps. Amanda Chiproot is thanked for digitising. Ross Sherlock, Alan Armitage, Bill Davis, John Kerswill, Rob Berman, and Hamish Sandeman are thanked for stimulating discussions.

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