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GS-7 Hydrothermal alteration and metamorphism of the Sherridon structure, Sherridon area, Manitoba (part of NTS 63N3)

by D.K. Tinkham and N. Karlapalem

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The following figures have been revised:

Figure GS-7-3: “Trace-element classification diagram based on relatively immobile element ratios for the main rock types in the field area, excluding pegmatite and late intrusive rocks (boundaries from Pearce, 1996)” **p.83**

Figure GS-7-4: “Chondrite-normalized rare earth element profiles for **a)** least-altered samples from the garnet-cordierite-sillimanite-biotite gneiss (GCSB) unit (circles) and paleosome from the migmatitic gneiss unit (triangles) that do not contain obvious leucosome in hand sample; **b)** altered samples from the GCSB with relatively high SiO_2; two samples with higher $(La/Yb)_N$ are dashed for clarity; **c)** samples from the biotite-bearing to biotite quartzofeldspathic gneiss subunit (BQG) with no apparent premetamorphic hydrothermal alteration, except for possible silicification; and **d)** typical garnet-biotite gneiss unit samples. Chondrite-normalization values are from Boynton (1984).” **p.84**

Figure GS-7-5: “High-field-strength-element ratio tectonic discrimination diagrams for rhyolite in VMS settings (from Schandl and Gorton, 2002): **a)** Th/Ta versus Ta/Yb plot; **b)** Th-Hf versus Ta/Hf plot. The diagrams show that ratios of the garnet-biotite gneiss are distinctly different from those of other felsic gneisses likely derived from rhyolite or dacite. Abbreviations: ACM, active continental-margin; MORB, mic-ocean ridge basalt; WPB, within-plate basalt; WPVZ, within-plate volcanic zones.” **p.85**

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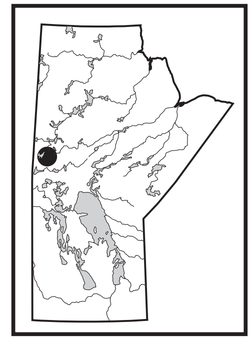

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Summary

Premetamorphic hydrothermal alteration of Paleoproterozoic rocks is widespread in the map area and consists of sericite and chlorite alteration of a silica-rich protolith, likely of rhyolitic composition. Carbonate-rich and calcsilicate rocks are interpreted to have developed dominantly from carbonate-altered mafic rocks (basalt or gabbro). Least-altered protoliths of silica-rich rocks are peraluminous, and trace-element chemistry is compatible with that of most silica-rich gneiss that has formed in a volcanic-arc environment. Regional metamorphism in the Sherridon structure reached upper-amphibolite–facies conditions in the sillimanite stability field, as constrained by the occurrence of partial melting in garnet–cordierite–sillimanite–biotite–plagioclase–K-feldspar–quartz stromatic migmatite gneiss. Alteration, lithogeochemical, geochronological and metamorphic studies are in progress to constrain the environment in which volcanogenic massive sulphide deposits of the Sherridon structure formed, and to constrain the metamorphic evolution of the structure.

Introduction

In 2008, the authors conducted targeted geological mapping in the Sherridon structure, located approximately 60 km northeast of Flin Flon, to support a study investigating the lithostratigraphy, hydrothermal alteration, deformation and metamorphism of a suite of rocks associated with Paleoproterozoic volcanogenic massive sulphide (VMS) deposits. This study is supported through the federal government's Targeted Geoscience Initiative 3 program. Mapping concentrated on extending an area mapped by the first author in 2007 (Fidelity zone) and on new mapping in an area 3 km to the southwest in a zone of known massive sulphide mineralization (Lost and Cold lakes zones). The results of mapping in the Fidelity zone from the 2007 and 2008 field seasons are presented, along with a summary and integration of the geological mapping with petrographic analysis and lithogeochemistry results from the 2007 season.

Regional geology

The field area is located within the Paleoproterozoic Sherridon structure in the Sherridon–Hutchinson Lake Complex on the south flank of the Kisseynew Domain (Zwanzig, 1999), and is of economic interest because of known massive sulphide mineralization near the community of Sherridon. The Sherridon structure is part of a series of regional-scale nappe-like structures in the Trans-Hudson Orogen that formed during 1.82–1.80 Ga compression and high-temperature metamorphism (Zwanzig, 1999), and consists dominantly of upper-amphibolite–facies gneiss (metavolcanic and possibly metasedimentary rocks) and local intrusive rocks (Bateman and Harrison, 1946; Froese and Goetz, 1981; Zwanzig, 1999). Amphibolite-facies metavolcanic and metasedimentary gneisses in the Sherridon structure are surrounded by a suite of 1.87–1.85 Ga arc plutonic rocks (Machado et al., 1999). This package of amphibolite-facies gneiss is hereafter referred to as the 'Sherridon Complex' (Figure GS-7-1).

Previous mapping in the western half of the Sherridon Complex and the field area discussed here includes that of Bateman (1945), Bateman and Harrison (1946), Goetz (1980) and Froese and Goetz (1981). Correlation of stratigraphy in the Sherridon Complex with surrounding stratigraphy has been problematic and debated, and recent interpretations suggest that at least part of the quartz-rich, 'pelitic', calcareous, and amphibolitic gneisses of the Sherridon Complex are equivalent to the Amisk Group (Zwanzig and Schledewitz, 1992; Ashton and Froese, 1998) of the Flin Flon Belt. The dominant rock types in the region include silica-rich biotite quartzofeldspathic gneiss derived from rhyolite and dacite (Syme et al., 1998), calcsilicate rocks and carbonate gneiss, biotite gneiss with common metapelitic mineralogy, a variety of amphibolite, and relatively late mafic–ultramafic intrusive rocks (Bateman and Harrison, 1946; Goetz, 1980; Froese and Goetz, 1981). The central portion of the Sherridon Complex contains relatively homogeneous garnet-biotite gneiss that has an uncertain age and origin.

Geology of the Fidelity zone

The Fidelity zone lies in the central portion of the Sherridon Complex (Figure GS-7-2). The dominant structure in the map area is the reclined Sheila Lake fold, which has a north-striking axial surface dipping moderately to the east and a fold axis calculated as plunging approximately 40°E in the immediate field area. The Sheila Lake fold was interpreted by Zwanzig (1999) as a regional F_3 generation fold with a shallower plunging fold

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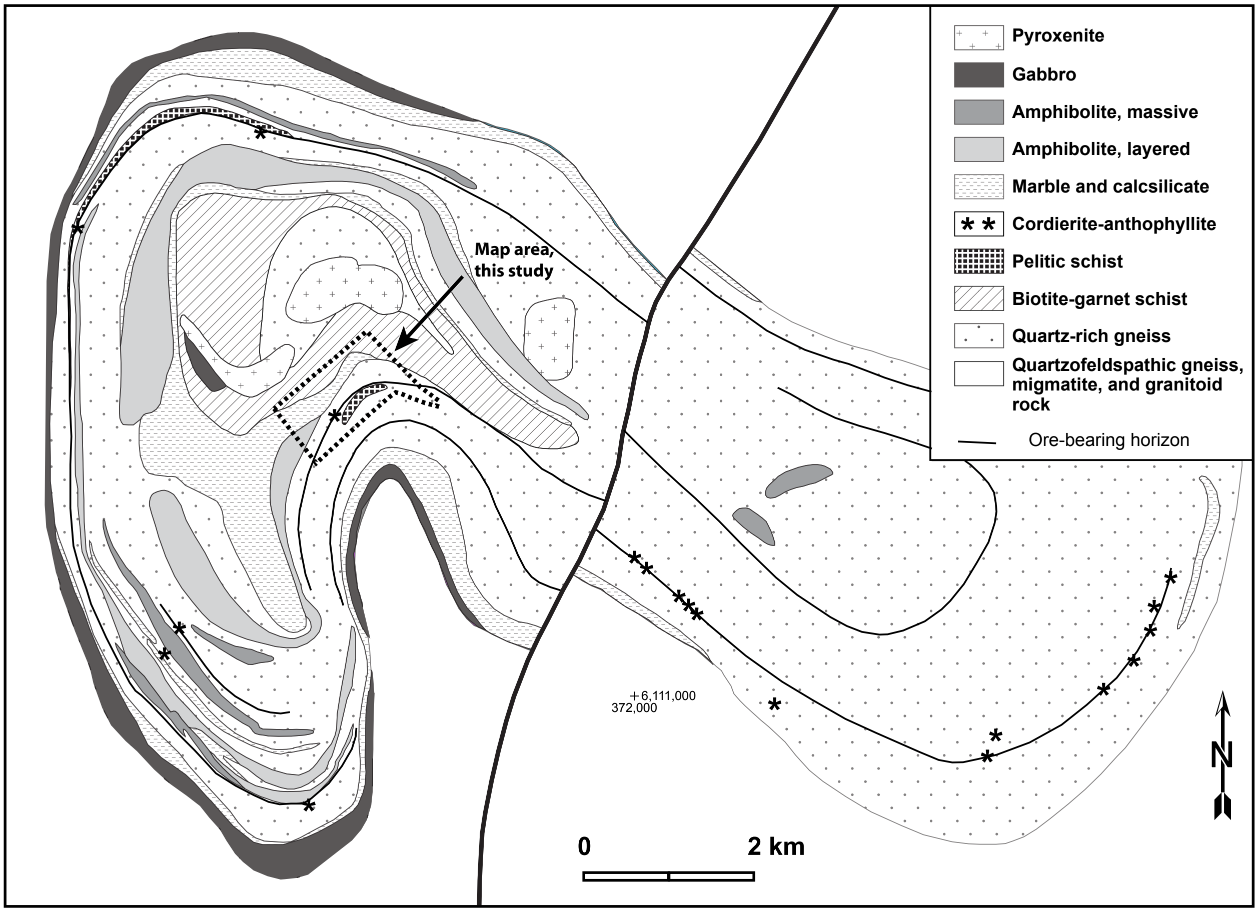

*Figure GS-7-1: Geology of the Sherridon Complex, showing the location of the map area, major lithological units and known locations of cordierite+anthophyllite considered to represent metamorphosed hydrothermal alteration (*from *Froese and Goetz, 1981).*

axis of 25°E. The 40° plunge reported here was calculated using the dominant foliation from only the northern two-thirds of the map area to best approximate the orientation of the fold axis in the vicinity of known mineralization in the northern part of the map area. The dominant outcrop-scale structure is dominated by folding; outcrop- and map-scale faults were not observed.

Geological map units

The high amount of strain and degree of metamorphic recrystallization have destroyed all primary features in the field area, making unambiguous interpretation of protolith in the field essentially impossible in most cases. Map units were therefore developed on a purely mineralogical, rock association and textural basis. Although all but one of the major geological map units are heterogeneous in detail, they are all well defined based on mineralogy (including mode) and rock association. Rock texture is a useful guide for some of the units, but never defines a geological unit. Mapping based on mineralogy in a sequence of rocks that has experienced premetamorphic hydrothermal alteration results in map units that partially reflect the nature of hydrothermal alteration and partially the original protolith where alteration was weak. Some units have gradational contacts over 10–50 m, which may, in part, reflect premetamorphic hydrothermal alteration.

Garnet-biotite gneiss

The dominant rock type of this unit (informally called the 'Bob gneiss') is a garnet-biotite±hornblende gneiss that is medium to coarse grained, mesocratic to melanocratic, black to medium grey and characterized by subhedral, 2–5 mm, homogeneously distributed red garnets. Compositional layering is moderate to weak, defined by varying biotite and hornblende content. Graphite is locally abundant (up to 3%) at the southwest end of Jonah Lake near the contact with the graphitic biotite quartzofeldspathic gneiss unit. The contact with this unit is gradational.

Graphitic biotite quartzofeldspathic gneiss

This unit is very poorly exposed and consists of graphitic biotite gneiss, biotite gneiss and locally biotite-bearing gneiss with a granitic to pegmatitic texture. These rocks are leucocratic to mesocratic, white to buff to grey-green, commonly oxidized and showing a red to orange weathering colour, and dominantly medium grained (locally coarse to very coarse). Amphibole is

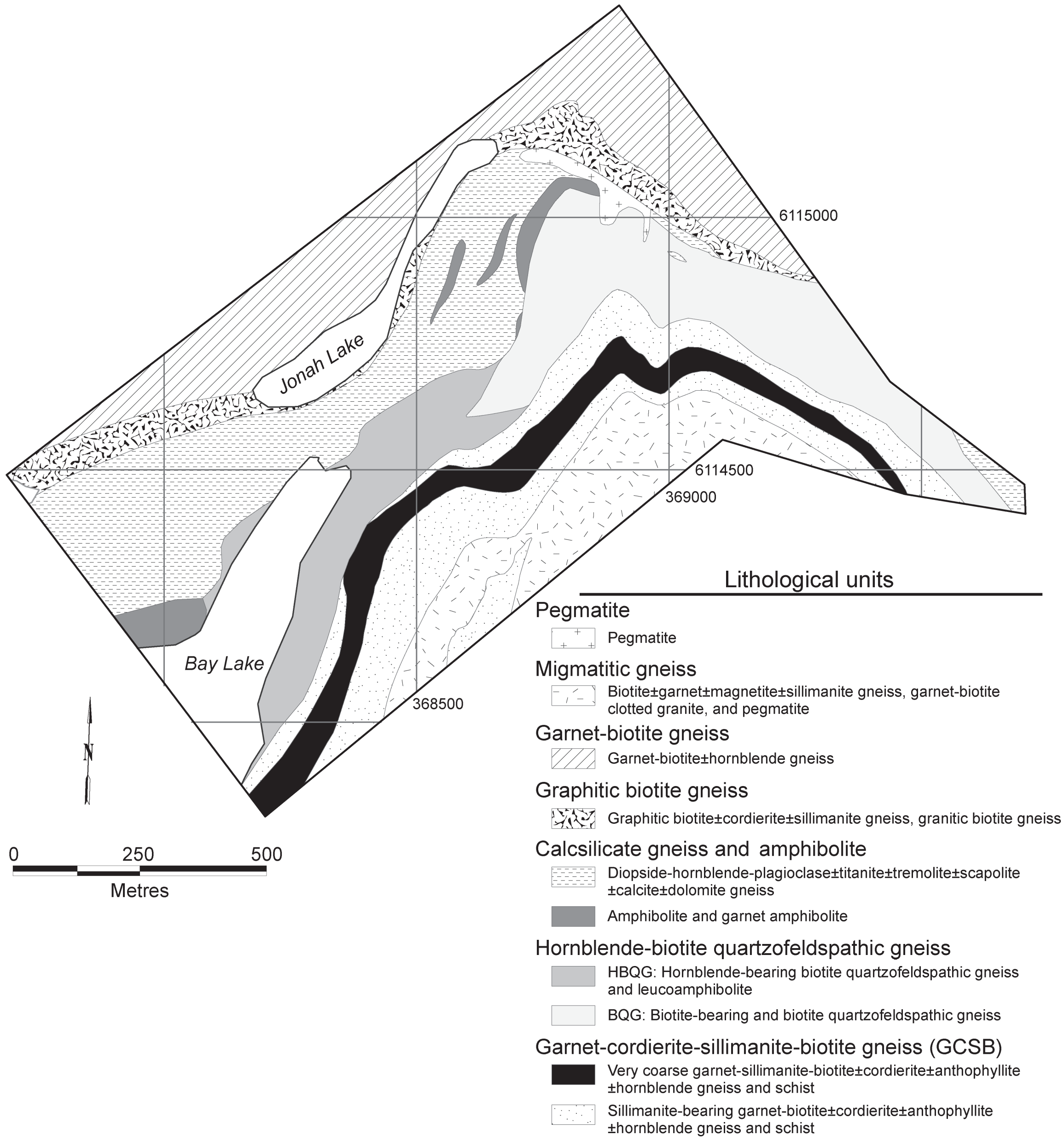

Figure GS-7-2: *Geology of the map area, based on 2007 and 2008 mapping. Map units are based on metamorphic rock types and therefore reflect a combination of original stratigraphy and hydrothermal alteration.*

locally present, and local sulphide concentrations up to 3% near contacts with the calcsilicate gneiss and amphibolite unit are observed south of Jonah Lake. Interpreted metamorphosed alteration (cordierite-anthophyllite±sillimanite gneiss) is observed on the east side of Jonah Lake in the contact zone with the calcsilicate gneiss and amphibolite unit.

Calcsilicate gneiss and amphibolite

This unit is variable and characterized by widespread carbonate-bearing rocks. The dominant rock type is a hornblende-plagioclase-quartz±scapolite±titanite±carbonate±tremolite±diopside calcsilicate to carbonate-silicate gneiss with local ±carbonate±garnet amphibolite layers or lenses. Foliation is weak to moderate and defined by diffuse layers of concentrated amphibole. Calcsilicate and carbonate-silicate gneiss is buff to medium grey-green and coarse to locally very coarse, with plagioclase content typically 35–60% and hornblende content typically <35%. Amphibolite and garnet amphibolite are melanocratic and medium to coarse grained, with hornblende typically >50% and subhedral red garnet (<5 mm). Local leucoamphibolite is carbonate bearing, with coarse garnet (up to 4 cm) and hornblende (up to 5 cm). Layers of biotite±hornblende gneiss and anthophyllite-rich rock are locally present. Petrographic analysis indicates that most of the carbonate in this unit is coarsely crystalline and in apparent equilibrium with many of the peak metamorphic minerals, indicating that calcite was introduced prior to metamorphism. The association with hornblende-rich rocks in the majority of the unit and the variable amounts of carbonate, scapolite, and tremolite over short distances are compatible with the interpretation that much of this unit represents intense regional carbonate alteration of a mafic protolith. The presence of several layers of pristine amphibolite and garnet amphibolite with very minor to no carbonate phase is compatible with emplacement of these bodies as post–carbonate-alteration mafic dikes or sills.

Hornblende and biotite quartzofeldspathic gneiss

This unit is dominated by a generally leucocratic, medium- to coarse-grained felsic rock, and is subdivided into two subunits: biotite-bearing and biotite quartzofeldspathic gneiss (BQG) and hornblende-bearing biotite quartzofeldspathic gneiss (HBQG). This unit contains the least amount of mafic phases near the hinge of the main Sheila Lake fold structure, with mafic content increasing to the east and southwest, and local biotite+anthophyllite occurrences. The BQG subunit is locally very quartz rich (estimated at >70%) and locally plagioclase rich (estimated at >60%), but typically consists of subequal portions of quartz and feldspar. It is light grey to buff to light pink, with biotite generally <3% and locally <0.5%. Petrographic analysis indicates that this subunit locally contains up to 15% nonporphyroblastic cordierite that is very difficult to identify in hand sample. The subunit generally shows an increase in biotite content towards the eastern end of the field area, where it becomes biotite gneiss with 7–10% biotite. The HBQG is leucocratic to mesocratic and light to medium grey, and generally contains hornblende. The HBQG grades into a plagioclase-rich leucoamphibolite at the south end of the field area.

Garnet-cordierite-sillimanite-biotite gneiss (GCSB)

This unit is subdivided based on mineral mode, which tends to correlate with grain size, and is characterized by the common association of coexisting garnet+biotite+sillimanite±cordierite±amphibole (hornblende and/or anthophyllite or cummingtonite). The central portion of the unit is typically very coarse grained and locally contains abundant and very coarse sillimanite (as fibrolitic clusters to prismatic crystals), whereas the outer portions of the unit are dominantly medium grained and have higher biotite content, less garnet and much less sillimanite (typically from <2% to 3% fibrolite). Petrographic studies indicate that, locally, cordierite and sillimanite are intimately associated with each other, with preferentially aligned sillimanite occurring as inclusions within, and at the margins of, cordierite crystals. Cordierite is very difficult to identify in the field because it does not occur as a porphyroblastic phase in most rocks. Garnet porphyroblasts (up to 5 cm) and sillimanite-rich porphyroblasts and fibrolite-rich clusters (up to 2 cm) are commonly observed in the very coarse subunit. Rocks with no sillimanite are widespread but of low abundance. Foliation-concordant lenses <1 m wide, consisting of coarse biotite- and anthophyllite-rich rock and amphibolite, are continuous over a distance of 100 m. Most rock types contain visible sulphides (typically pyrite or pyrrhotite), ranging from <1% to 2%.

Migmatitic gneiss

The migmatitic gneiss unit contains three dominant rock types: massive, medium- to coarse-grained, biotite-bearing granite to granodiorite with local 1–4 cm biotite-rich clots; medium- to coarse-grained biotite–K-feldspar–plagioclase–quartz±garnet±sillimanite±cordierite gneiss; and coarse- to very coarse grained granitic pink pegmatite. The contact with the adjacent garnet-cordierite-sillimanite-biotite gneiss is locally gradational, characterized by the presence of a stromatic migmatite fabric that developed during partial melting of the garnet-cordierite-sillimanite-biotite gneiss. Concordant leucosome with biotite-rich melanosome locally passes continuously into discordant pink pegmatite, and some of the pink pegmatite within this unit is therefore interpreted to be derived from partial melting of the garnet-sillimanite-biotite gneiss. The massive biotite-bearing granite to granodiorite contains rounded biotite-rich clots that also contain sillimanite, cordierite and remnant garnet. These clots are likely derived from the nearby partially melted hostrock.

Hydrothermal alteration

The intensity and distribution of premetamorphic hydrothermal alteration are difficult to determine in the field because of the combined intensity of deformation and high-temperature metamorphism. Deformation and metamorphic recrystallization have destroyed nearly all textures and fabric that are commonly used to determine the nature of the rock protolith in some map units. A study is in progress that combines lithogeochemistry, petrography and calculation of alteration indices to constrain the nature of alteration. Alteration indices were calculated using the method of Piche and Jebrak (2004). The technique uses a normative mineral recalculation to determine indices for sericite, paragonite, pyrophyllite and chlorite alteration. Preliminary results, provided in Tables 1 and 2 of Data Repository Item DRI2008004,[2] are compatible with a large portion of the garnet-cordierite-sillimanite-

[2] MGS Data Repository Item DRI2008004, containing the data or other information sources used to compile this report, is available online to download free of charge at http://www2.gov.mb.ca/itm-cat/freedownloads.htm, or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Science, Technology, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada.

biotite gneiss unit, having been derived from a sericite- and chlorite-altered protolith. Detailed alteration studies are still in progress.

Lithogeochemistry

Lithogeochemistry studies are in progress to aid in identification of protolith, correlation of different rock types and calculation of hydrothermal alteration indices. Whole-rock major- and trace-element data were obtained on 50 surface samples. Major- and trace-element analyses were carried out by Activation Laboratories Ltd. using a lithium metaborate/tetraborate fusion followed by acid dissolution and inductively coupled plasma–mass spectrometry (ICP-MS) measurement. Trace-element analyses presented here were determined at Laurentian University using high-temperature acid-bomb dissolutions for 5 days, followed by ICP-MS analysis. Halo Resources Ltd. provided an additional 153 analyses of drillcore samples in the area of the Fidelity zone; these were determined by ALS Chemex using lithium metaborate fusion and acid dissolution followed by ICP-MS. Only a subset of the data from the biotite-bearing quartzofeldspathic gneiss, garnet-cordierite-sillimanite-biotite gneiss, migmatitic gneiss and garnet-biotite gneiss units is presented in detail here (Data Repository Item DRI2008004, Table 1).

Samples were divided by geological map unit, subunit and lithology, and were plotted on a variety of major- and trace-element classification diagrams. The alumina saturation indices of the least-altered felsic samples all indicate they are peraluminous. The immobile element Nb/Y versus Zr/Ti diagram of Pearce (1996) classified the majority of biotite-bearing quartzofeldspathic gneiss (BQG) and garnet-cordierite-sillimanite-biotite gneiss (GCSB) samples in the 'rhyolite/dacite field', and the four garnet-biotite gneiss samples cluster within the 'andesite, basaltic andesite' field (Figure GS-7-3). The calcsilicate

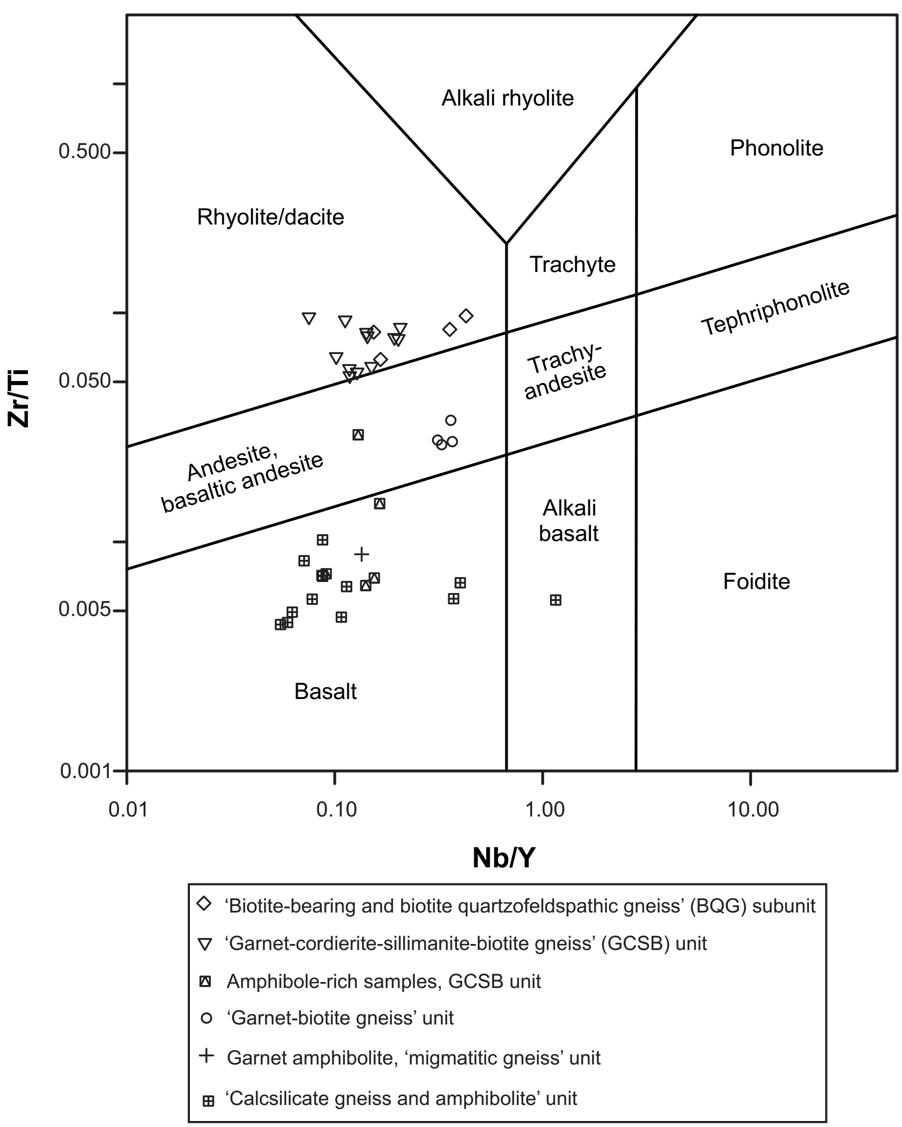

***Figure GS-7-3:** Trace-element classification diagram based on relatively immobile element ratios for the main rock types in the field area, excluding pegmatite and late intrusive rocks (boundaries* from *Pearce, 1996).*

gneiss and amphibolite samples and amphibole-rich samples from the GCSB are classified as 'basalt' and 'alkali basalt', and are shown for reference.

Chondrite-normalized rare earth element plots for the BQG (Figure GS-7-4c) yield relatively flat profiles with element concentrations generally <10 times chondrite values, with the exception of one sample that contains garnet and trace amounts of sillimanite. This sample has slightly elevated heavy rare earth element (HREE) concentrations, with higher La and Ce values than other samples from this unit. Based on the presence of sillimanite and garnet, it is possible that this sample has experienced premetamorphic hydrothermal alteration. The other three samples do not contain sillimanite or garnet (although rare garnet was noted in outcrop for one of the samples) and minor hornblende is present in one sample. The GCSB is characterized by a negative Eu anomaly and higher HREE content than the BQG. Alteration indices and lithology were used to separate samples from this unit into least-altered and altered groups. The least-altered samples (Figure GS-7-4a) show relatively consistent REE profiles, with relatively low $(La/Yb)_N$ ratio. In comparing these profiles to rhyolite from Flin Flon and Snow Lake, the pattern shown here is similar to those from the Flin Flon mine rhyolite (Syme et al., 1999, Figure 9c). The altered GCSB (Figure GS-7-4b) contains one sample with an anomalously high LREE content and two with low HREE. The gneissic rocks of the GCSB are distinctly different from those of the BQG in their REE profiles, as indicated by the Eu anomalies, and it is not certain if this is accentuated by alteration or if it is entirely a primary igneous signature. This unit has low Na_2O and CaO and high FeO and MgO relative to the BQG, compatible with plagioclase feldspar destruction. However, the least-altered samples from this unit have similar REE patterns to the altered samples, suggesting that the Eu anomaly reflects plagioclase fractionation and not alteration. The garnet-biotite gneiss (Figure GS-7-4d) yields a consistent REE pattern with a significantly larger $(La/Yb)_N$ ratio and an insignificant Eu anomaly.

The granite tectonic classification diagrams of Pearce

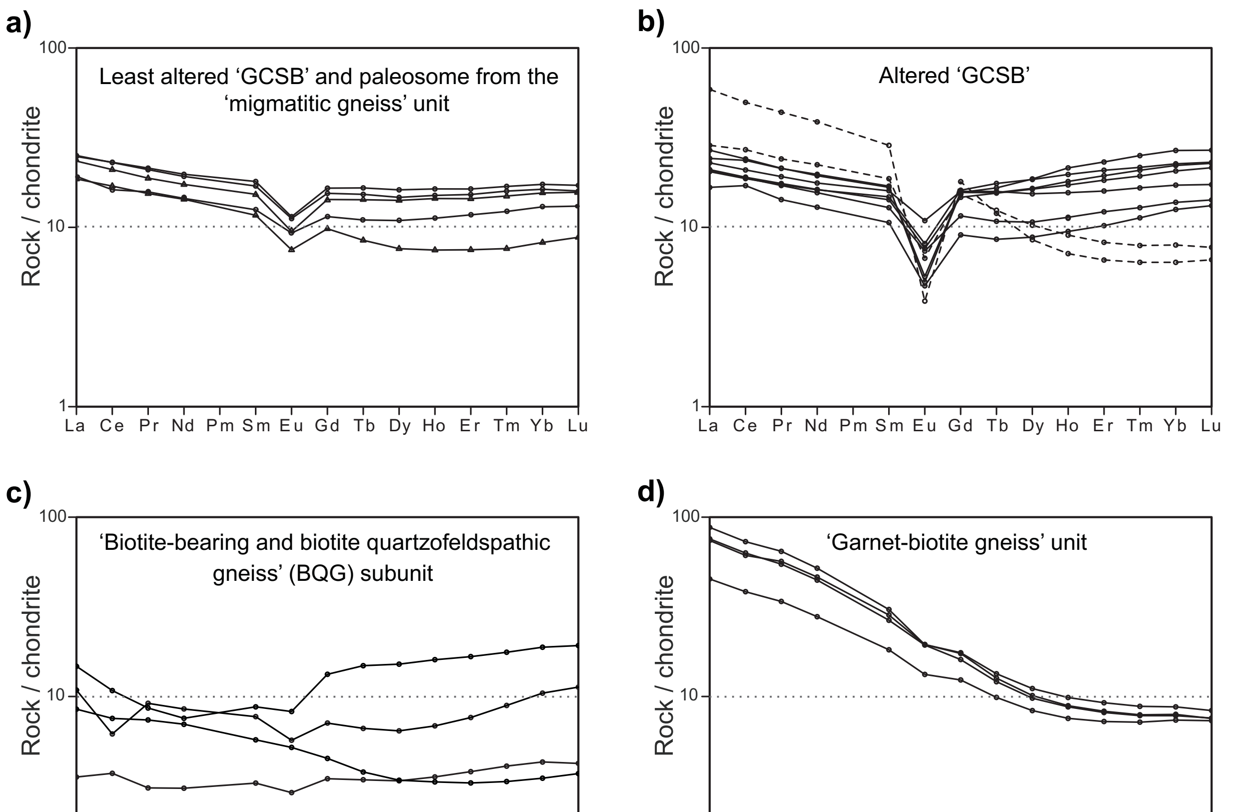

Figure GS-7-4: *Chondrite-normalized rare earth element profiles for* ***a)*** *least-altered samples from the garnet-cordierite-sillimanite-biotite gneiss (GCSB) unit (circles) and paleosome from the migmatitic gneiss unit (triangles) that do not contain obvious leucosome in hand sample;* ***b)*** *altered samples from the GCSB with relatively high SiO_2; two samples with higher $(La/Yb)_N$ are dashed for clarity;* ***c)*** *samples from the biotite-bearing to biotite quartzofeldspathic gneiss subunit (BQG) with no apparent premetamorphic hydrothermal alteration, except for possible silicification; and* ***d)*** *typical garnet-biotite gneiss unit samples. Chondrite-normalization values are from Boynton (1984).*

et al. (1984), based on the assumed immobile elements Nb, Y, Ta and Yb, indicate that the GCSB, BQG, garnet-biotite gneiss and paleosome of the migmatitic gneiss all have volcanic-arc signatures. High-field-strength-element ratios from the same suite of samples were calculated and plotted on the tectonic discrimination diagrams of Schandl and Gorton (2002), developed for rhyolite in VMS settings (Figure GS-7-5a). The results show moderate scatter but, on the Th/Ta versus Ta/Yb diagram, the garnet-biotite gneiss samples all plot in the active continental-margin field, the GCSB samples straddle the boundary between the active continental-margin and within-plate volcanic fields, and the BQG samples range from the active continental-margin field to the mid-ocean ridge basalt field. The garnet-biotite gneiss samples plot in a tight cluster, reflecting the homogeneous nature of this unit, and they have higher ratios than all other samples. In the Th/Hf versus Ta/Hf plot (Figure GS-7-5b), the garnet-biotite gneiss samples again plot in a tight cluster in the active continental-margin field, the GCSB straddles the boundary between the active continental-margin and within-plate volcanic fields, and the BQG samples define a trend towards higher Ta/Hf values into the within-plate volcanic field.

The rhyolite discrimination diagrams of Schandl and Gorton (2002) were developed using VMS-related Archean and post-Archean rhyolites from twelve belts throughout the world. Under the assumption that the chemical character of rhyolite has not changed significantly since the Archean, differences in the relative HFSE abundances and ratios reflect fractionation and tectonic environment (subduction environment at higher Th/Hf). They suggest that the higher Th/Hf of post-Archean rhyolites reflects input of Th via subduction-slab fluids with time, and that Archean VMS rhyolites therefore formed dominantly in rift environments. At any given Ta/Hf value, the more fractionated rocks within a belt have higher Th/Hf values. In a Th-Ta-Hf diagram, the felsic rocks detailed here show a wide range of Th/Hf at low Ta/Hf. The BQG has the lowest Th/Hf values, the GCSB has intermediate values and the garnet-biotite gneiss (technically not a rhyolite) has the highest values. The difference in HFSE, as illustrated in the Schandl and Gorton (2002) diagrams and the Eu anomalies and elevated LREE of the GCSB, is compatible with the magma source for the GCSB being more fractionated than that for the BQG. As well, the low Th/Hf and trend to higher Ta/Hf of the BQG might point to a slightly different environment of formation, but more analysis is needed to determine this. Analysis of the lithogeochemistry data provided by Halo Resources Ltd. is in progress to help determine this possibility. Using the arguments of Schandl and Gorton (2002)

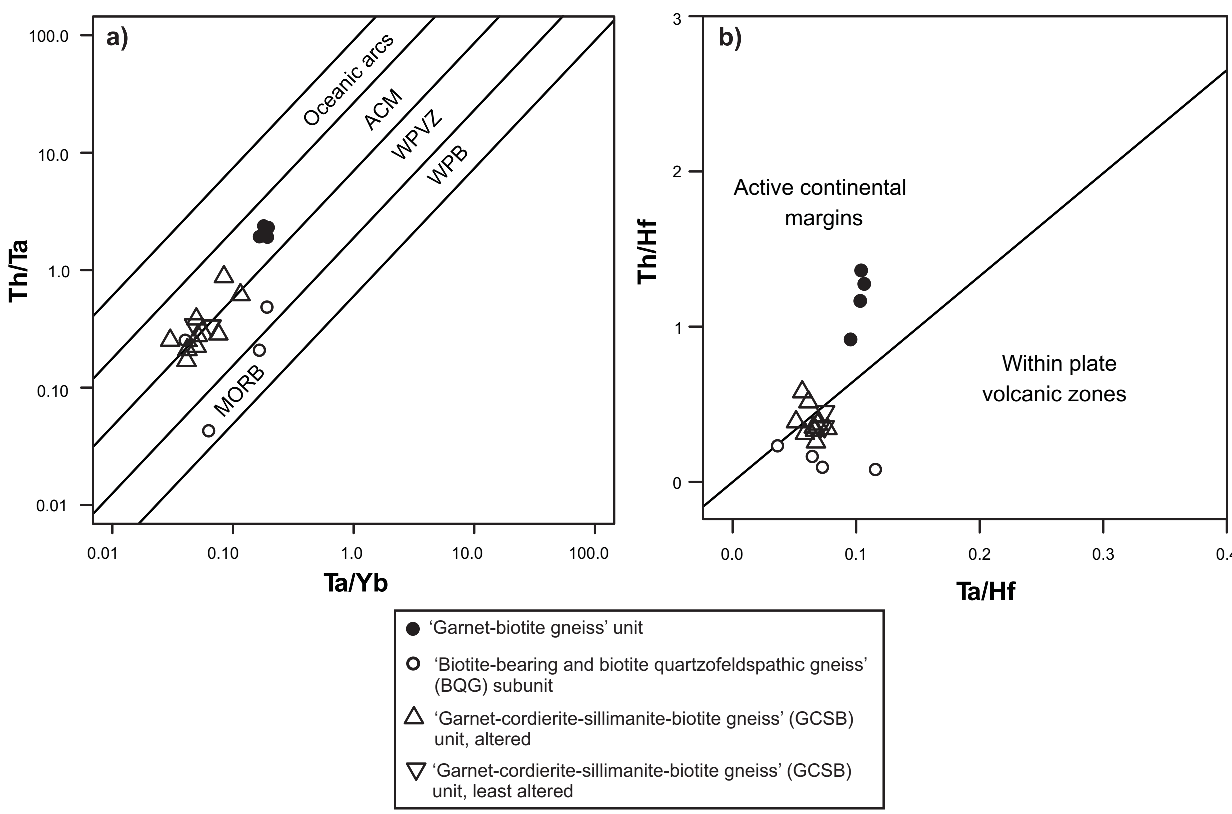

Figure GS-7-5: *High-field-strength-element ratio tectonic discrimination diagrams for rhyolite in VMS settings (*from *Schandl and Gorton, 2002):* ***a)*** *Th/Ta versus Ta/Yb plot;* ***b)*** *Th/Hf versus Ta/Hf plot. The diagrams show that ratios of the garnet-biotite gneiss are distinctly different from those of other felsic gneisses likely derived from rhyolite or dacite. Abbreviations: ACM, active continental-margin; MORB, mic-ocean ridge basalt; WPB, within-plate basalt; WPVZ, within-plate volcanic zones.*

and their HFSE diagrams, the garnet-biotite gneiss, if magmatic in nature, formed in an active arc environment, possibly in a subduction environment.

Economic considerations

Mapping in the Fidelity zone at a scale of 1:2500 has revealed that the zone of metamorphosed hydrothermal alteration characterized by garnet-cordierite-sillimanite-biotite±amphibole gneiss and interlayered amphibolite is much larger and continuous than previously realized. This zone of alteration is associated with several occurrences of cordierite-anthophyllite that likely represent more intense levels of chlorite alteration and are locally bordered by a silica-rich quartzofeldspathic unit that likely has a rhyolitic protolith with slightly different trace-element characteristics, although a sedimentary component cannot yet be ruled out. In addition, petrographic analysis has shown that cordierite and sillimanite are much more abundant in the quartzofeldspathic gneisses than previously realized. The presence of cordierite+sillimanite in these rocks is possibly related to a weak hydrothermal alteration that may or may not be associated with sulphides. Work is underway to constrain the significance of cordierite+sillimanite in these otherwise mineralogically simple quartzofeldspathic gneisses.

This study has also documented a wide zone that is best interpreted as a zone of intense carbonate alteration of a dominantly mafic protolith, which presumably developed at fairly shallow and cool levels in the sub–sea-floor environment. Differences in whole-rock chemistry (not presented here) and lack of carbonate alteration in some amphibolite of this unit suggest the presence of mafic sills or dikes emplaced in the post-alteration environment. Characterizing these amphibolitic rocks is important in developing an understanding of the changing conditions in the evolution of magmatic systems associated with the Sherridon Complex. Continued studies will help define the lithostratigraphy, alteration and metamorphic history of the belt, knowledge of which is important in development of mineral exploration strategies.

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