Current Research (2018) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 18-1, pages 71-93

GENESIS OF CARBONATE-HOSTED Zn MINERALIZATION IN THE HARE BAY AND PISTOLET BAY AREAS, GREAT NORTHERN PENINSULA, NEWFOUNDLAND

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ABSTRACT

The Hare Bay area of the Great Northern Peninsula hosts numerous carbonate-hosted Zn occurrences, including the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect. The mineralization occurs in crackle breccia (a type of collapse breccia), and in pseudobreccias, formed by the selective replacement of fabrics in the host rocks. Previous work has suggested that these occurrences are geologically similar to mineralization at the Daniel's Harbour Deposit.

Detailed petrographic, geochemical (whole-rock geochemistry, Electron probe micro analyser (EPMA)) and isotopic (S and Pb) studies were used to investigate the chemistry of the mineralizing fluid(s), origin of the fluid(s) and metals, and timing of mineralization, so as to generate a genetic model that could be used in regional exploration. Whole-rock geochemical and EPMA data indicate that metal contents vary between occurrences, and where mineralization origin is related to the mixing of metal-bearing fluids with sulphur-bearing fluids that contained elevated Cd and Fe contents. Lead isotope data suggest that the metals had a crustal source, having been leached from the Grenvillian basement or the overlying sedimentary rocks by hydrothermal fluids. These fluids migrated through the St. George Group carbonates along Acadian thrust faults and earlier structures associated with Taconic deformation. In suitably porous dolomite horizons, these metal-bearing fluids would have encountered a reduced sulphur source, likely related to Paleozoic seawater expelled from the sedimentary sequence during deformation and dehydration. Sulphur isotope data show that ore precipitation occurred as a result of thermochemical sulphate reduction at temperatures in excess of 100°C.

Future exploration should focus on suitably porous dolomite horizons, with special emphasis on structures that may have been conduits for fluid flow. The presence of well-developed pseudobreccias, over a strike length of more than 60 km, from Salmon River to North Boat Harbour, highlights the exploration potential of this area, and suggests that good potential exists for the discovery of orebodies that do not outcrop at the present erosional surface.

INTRODUCTION

Previous exploration activity from the 1950s to 1990s led to the discovery of numerous Zn occurrences on the Great Northern Peninsula (GNP) of Newfoundland. With the exception of the former Daniel's Harbour Deposit (Newfoundland Zinc Mine with ~7 Mt @ 7.8% Zn mined between 1975 and 1990), none of these occurrences have been considered economic. This suggests that western Newfoundland is somewhat unusual, as Mississippi Valley-Type (MVT) deposits elsewhere in the world, similar to the Daniels' Harbour Deposit, typically occur in extensive districts (100s km^2) that contain several, to as many as 400, individual deposits (Leach *et al.*, 2005). In the Hare Bay area (NTS map areas 02M/12, 12P/01, 12P/08, 12P/09), a number of Zn occurrences were discovered during exploration in the 1960s and 1970s. The largest known occurrence is the Round Pond Deposit (non NI-43-101 resource of 400 000 tons @ 2% Zn; Born, 1983), with other significant occurrences at the Salmon River #6 and Twin Ponds prospects (Figure 1). All known occurrences in the Hare Bay area were discovered from soil anomalies, and the potential remains for the discovery of blind deposits (*i.e.*, not cropping out at the surface) in this area.

King and Conliffe (2017) demonstrated that the Round Pond Deposit and Twin Ponds and Salmon River #6 prospects have many geological similarities with the Daniels Harbour Deposit. In 2017, work continued to investigate the genesis of carbonate-hosted Zn (± Pb) occurrences

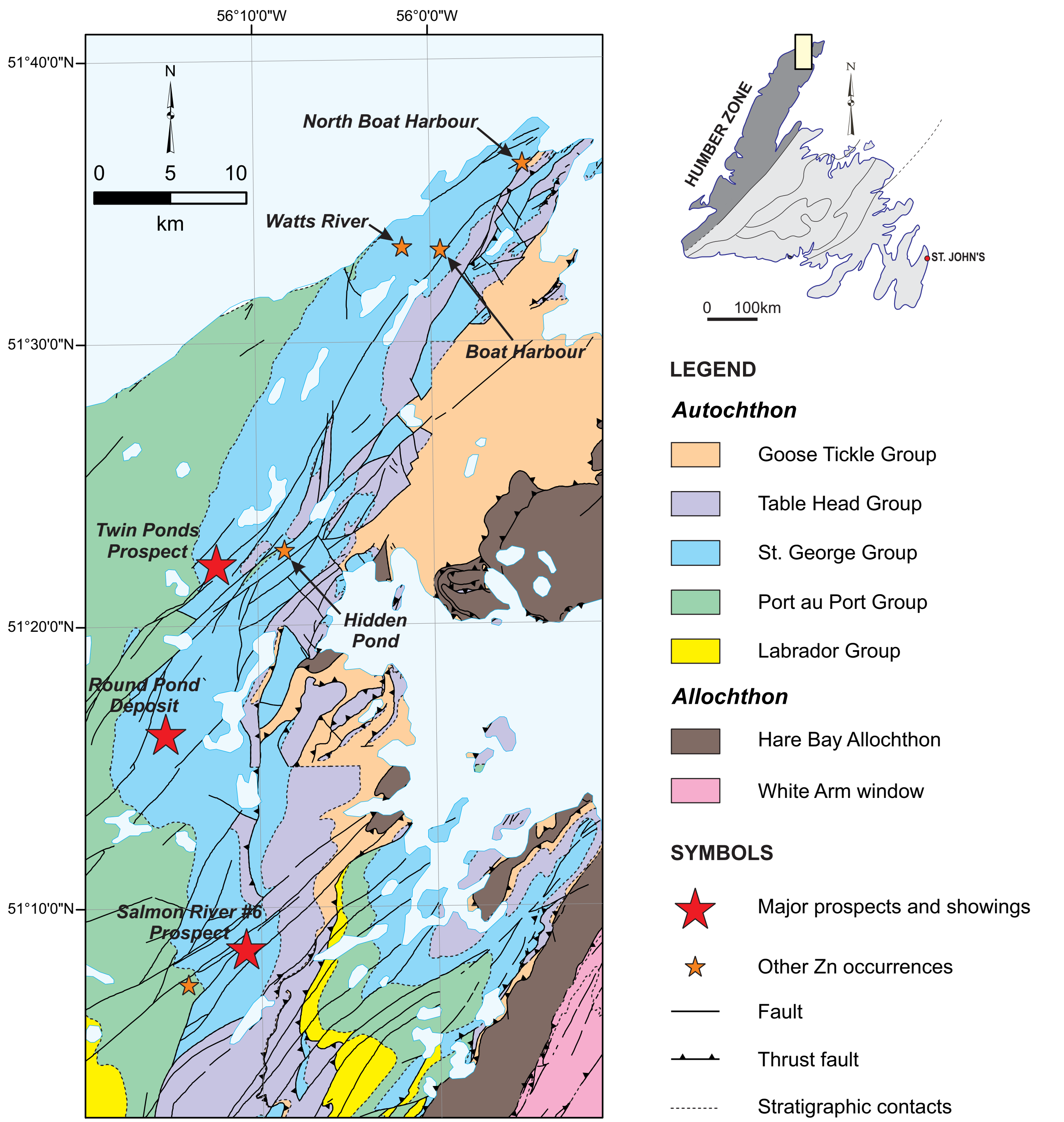

Figure 1. *Regional geological map of the Hare Bay area outlining the location of known Zn occurrences discussed in text (after Knight* et al.*, 1982; Knight and Edwards, 1986a, b; Knight* et al.*, 1986).*

in western Newfoundland, and included a recently completed B.Sc. (Hons.) thesis by Robert King at Memorial University (King, 2017). This report summarizes the geochemical (whole-rock and Electron probe micro analyser (EPMA) geochemistry) and isotopic (S, Pb) data from this thesis, and develops a genetic model that has implications for the direction of regional mineral exploration for carbonate-hosted Zn occurrences in western Newfoundland.

GEOLOGICAL SETTING AND PREVIOUS WORK

The geological setting of zinc occurrences on the GNP has been described in detail by King and Conliffe (2017) and King (2017), and is briefly summarized here. All occurrences are within autochthonous platform rocks of the Humber Zone, which were deposited on Grenville basement during the latest Neoproterozoic (~615 Ma) to Early Ordovician (~470 Ma). Basal rift-related terrestrial clastic and volcanic rocks of the Bradore and Forteau formations (Kamo *et al.*, 1989; van Staal and Barr, 2012; Figure 2) are unconformably overlain by clastic rocks of the Hawke Bay Formation. This, in turn, is overlain by a thick (~1.5 km) Cambrian to lower Ordovician carbonate platform succession (Port au Port and St. George groups; Figure 2), deposited on a passive margin to the south of Laurentia (James *et al.*, 1989). Progressive loading associated with the initiation of the Taconic Orogeny at *ca.* 490 Ma (Waldron *et al.*, 1998) led to the formation of a marine foreland basin and deposition of shallow- to deep-water carbonates and shales of the Table Head Group and muddy flysch of the Goose Tickle Group (James *et al.*, 1989; Figure 2).

Most major zinc occurrences in western Newfoundland are hosted by the St. George Group carbonate rocks. This ~500 to 600 m succession of subtidal and peritidal carbonate rocks was deposited as part of a broad low-energy platform during the Early to Middle Ordovician. The St. George Group is subdivided, in ascending order, into the Watts Bight, Boat Harbour, Catoche and Aguathuna formations (Figure 2; Knight and James, 1987). These represent sedimentation in a series of subtidal and peritidal environments that can be subdivided into two megacycles of Tremadocian and Arenigian age, reflecting changes in depositional environments in response to eustatic sea-level fluctuations and local tectonics (Knight and James, 1987). A significant unconformity separates the St. George Group and the overlying Table Head Group, termed the St. George Unconformity (Knight *et al.*, 1991).

These autochthonous sedimentary rocks were deformed during the Taconic Orogeny, when thin-skinned thrusting emplaced allochthonous rocks of the Humber Arm Allochthon (HAA) and the

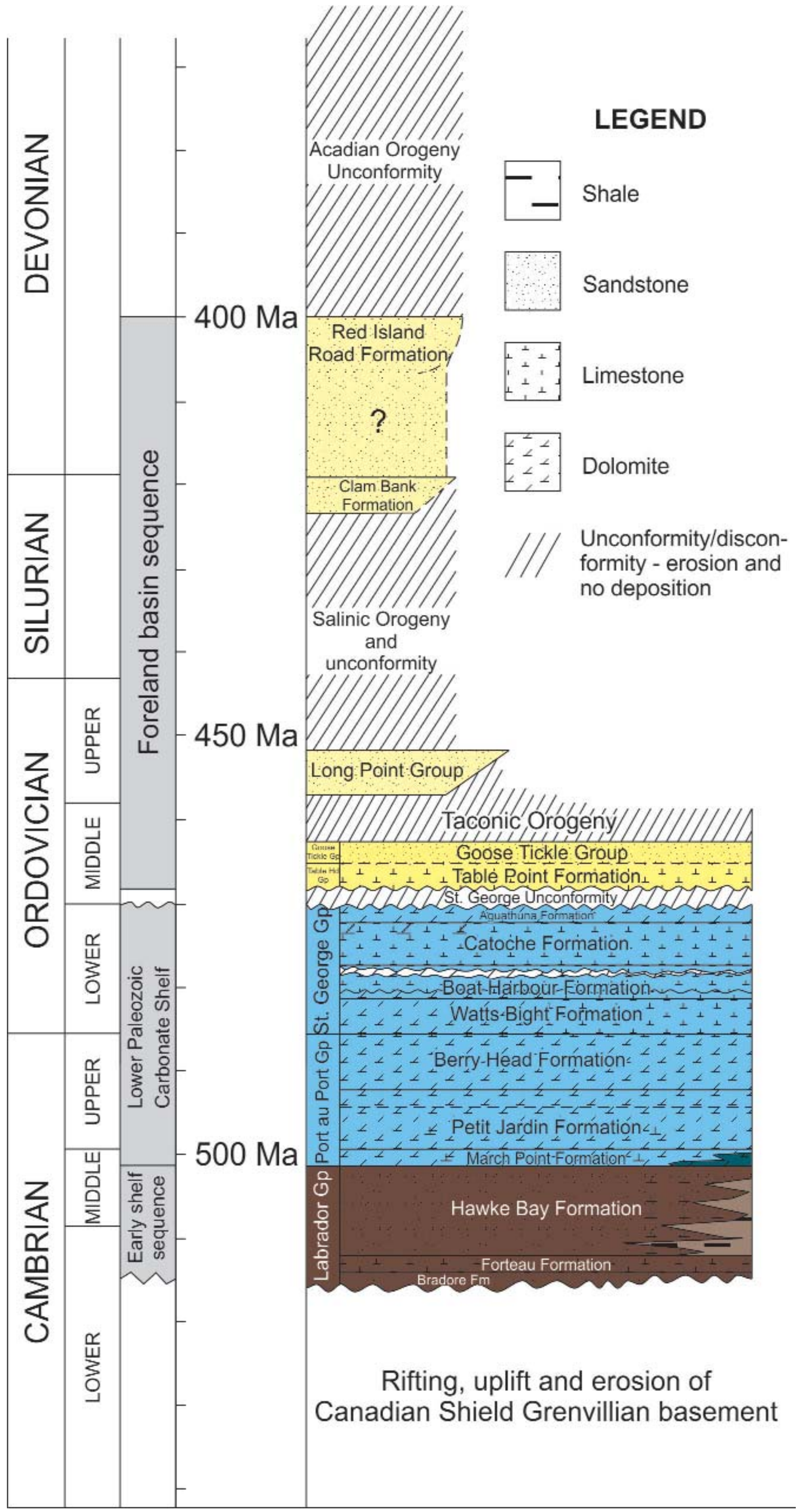

Figure 2. *Simplified stratigraphy of autochthonous lower Paleozoic sequences in western Newfoundland (adapted from Hinchey* et al.*, 2015).*

Hare Bay Allochthon (HBA) onto the Laurentian margin rocks (Cawood and Williams, 1988; Waldron *et al.*, 1998). Further deformation occurred during the Late Silurian to Early Devonian (Acadian Orogeny), including reactivation of thrust faults in the Humber Zone, including the Parsons Pond Thrust and the Round Head Thrust (Waldron *et al.*, 1998). Thrusting was thick skinned in these two major faults, as well as in the minor Long Range Thrust (Waldron and Stockmal, 1994; Stockmal *et al.*, 1998), and was responsible for the uplift of the Grenvillian basement rocks, which core the Long Range Mountains and the platform rocks.

PREVIOUS EXPLORATION

Exploration for Pb and Zn mineralization on the GNP began in the mid-1960s, spurred by the discovery of the Daniel's Harbour Deposit. Reconnaissance geochemical surveys, prospecting and geological mapping in the Hare Bay and Pistolet Bay areas resulted in the discovery of a number of Zn showings in rock types similar to those that host the Daniel's Harbour Deposit. The largest of these showings was in the Round Pond area, where diamond drilling in the 1970s returned grades up to 6.4% Zn over 3 m and outlined a potential Zn deposit 600 m north of Round Pond (Round Pond Deposit; Figure 1). Further exploration in the 1980s indicated that the Round Pond Deposit contained a non NI-43-101 adherent resource of 400 000 tons of ore grading 2% Zn (Born, 1983). A second zone, referred to as the Phillip's Zone, was discovered to the southeast of the main Round Pond Deposit, and diamond drilling outlined a non NI-43-101 adherent resource estimate of 98 266 tons at 1.5% Zn (Hutchings *et al.*, 1975).

Exploration activity outside of the Round Pond area has been limited, but a number of other significant showings have been identified. The Twin Ponds Prospect, located approximately 12 km north along strike from the Round Pond Deposit (Figure 1), was discovered in 1975 and trenching identified mineralization grading 1.42% Zn over 4.8 m (Cant and van Ingen, 1976a). Drilling at the Twin Ponds Prospect, however, did not intercept significant mineralization at depth, with only two holes containing any significant mineralization, grading 0.42% Zn over 5.4 m and 0.81% Zn over <1 m (Cant and van Ingen, 1976a). A number of zinc showings were reported from the Salmon River area, 15 km south of the Round Pond Deposit (Figure 1). The most developed of these is the Salmon River #6 Prospect, where samples from trenches assayed up to 16% Zn, 7.6% Pb and 0.4 oz. of Ag. However, drilling of the trenched area yielded poor results, indicating that mineralization was discontinuous (Dean, 1977).

Other prospective areas identified near Watts River, Hidden Pond and North Boat Harbour (Figure 1) were also explored in the 1970s and 1980s, with a number of soil geochemical anomalies identified. Trenching at North Boat Harbour identified significant zinc mineralization (grab samples up to 8.14% Zn; Cant and van Ingen, 1976b). Although follow-up drilling on these anomalies only identified low-grade (<1% Zn) mineralization over short intervals, it did recognize significant thicknesses of collapse breccia considered favourable for mineralization (Laforme, 1980; Burton, 1980; Leslie, 1981).

DEPOSIT DESCRIPTIONS

The following contains brief geological and petrographic descriptions of the three main prospects and deposits examined in 2016: the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect. More detailed descriptions of each showing, including geological maps and trench maps, are provided by Saunders *et al.* (1992), King and Conliffe (2017) and King (2017).

ROUND POND DEPOSIT

All occurrences in the Round Pond area are hosted by the Boat Harbour Formation, which consists of a basal dolomite and chert breccia unit that is overlain by a sequence of bioturbated micritic limestones, laminated limestones and dolostones and secondary dolomite (Knight, 1980). There are two main mineralized zones in the Round Pond area, the Main Zone (Plate 1A) to the northeast, and the Phillips Zone to the south (King and Conliffe, 2017), and a number of minor sphalerite showings (Knight *et al.*, 1986). The host rocks to mineralization are classified into two main types; angular fragments of tan, fine-grained dolomite in a white coarse-grained dolomitic cement (approximately 20% white spar), known as crackle breccia (Plate 1B, C), and grey dolomite with white dolomitic cement (approximately 10–20% white spar) referred to as pseudobreccia.

Surface outcrops consist mainly of crackle breccia, and petrographic analysis indicates that the sulphide mineralization is predominantly early, coarse-grained sphalerite around the dolomite clast margins (Plate 1C; Figure 3A, B). Galena occurs either as grains within sphalerite crystals, or in pore spaces between sphalerite crystals. Pyrite is also present and occurs as either disseminated grains in saddle-dolomite cement, or as grains within the dolomite clasts. SEM-MLA analysis also indicates the presence of a second generation of galena, which occurs in late quartz-K-feldspar veins that cut through all other mineral phases (Figure 3A).

Mineralized pseudobreccia is intersected in drillcore below the crackle breccia at the Main Zone. Fine- to medium-grained sphalerite occurs as disseminated grains in saddle-dolomite cement (Plate 1D). Pyrite occurs as medium-

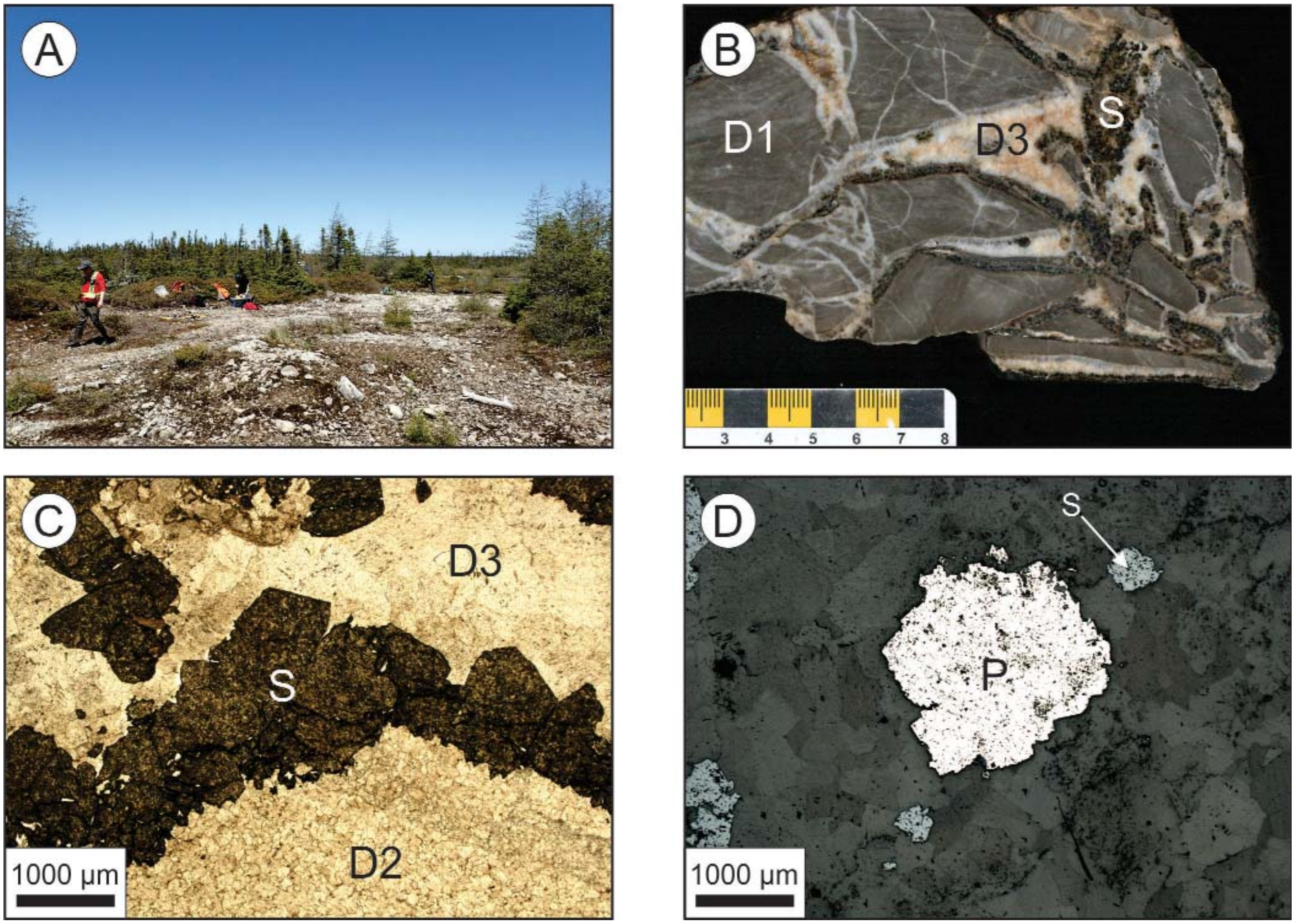

Plate 1. *Selected photographs and photomicrographs from Round Pond Deposit. A) Main Zone trench at Round Pond Deposit; B) Crackle breccia with angular clast of early dolomite coated by sphalerite and saddle dolomite, sample 16JC 026 A03; C) Photomicrograph of crackle breccia in sample 16JC 029A01 (Phillips Zone), with euhedral sphalerite coating dolomite clast and late saddle dolomite filling pores (plane-polarized light); D) Photomicrograph of pyrite and sphalerite crystals disseminated in saddle-dolomite cement in pseudobreccia, sample 16JC 026 A04 (reflected light). D2 – Medium-grained euhedral dolomite, D3 – Saddle dolomite, P – Pyrite, S – Sphalerite.*

to coarse-grained disseminations in the saddle-dolomite cement (Plate 1D), fine disseminated grains in chert fragments throughout the sample, and as pyrite-rich veinlets cutting dolomite clasts. Minor galena is generally associated with sphalerite in the saddle-dolomite cement or as veinlets crosscutting sphalerite grains, indicating that galena precipitation was relatively late in the paragenetic sequence.

TWIN PONDS PROSPECT

Mineralization was observed at two main locations in the Twin Ponds area, in an exploration trench (also known as the Wade Showing; trench map in Cant and van Ingen, 1976a) and in roadside outcrops along Route 430. Mineralization at the Wade Showing is hosted in fine- to medium-grained grey to cream Watts Bight Formation dolostone (Saunders *et al.*, 1992), whereas outcrops along the highway are hosted by the overlying Boat Harbour Formation (similar to the Round Pond Deposit).

The mineralization style is similar to that exposed at the Main Zone, Round Pond, with well-developed crackle breccia composed of angular, tan-grey dolomite and grey chert clasts cemented by coarse-grained, white dolomite (Plate 2A). Sphalerite occurs as fine- to medium-grained, subhedral crystals that form 1-mm-thick coatings on dolomite and chert clasts (Plate 2B). Pyrite is restricted to dolomite clasts, and likely predates the main mineralization event. Both dolomitic clasts and saddle dolomite are commonly crosscut by veinlets of quartz containing minor K-feldspar. In addition, roadside outcrops also indicate that moderately developed pseudobreccias (with 15–20% white dolomite spar)

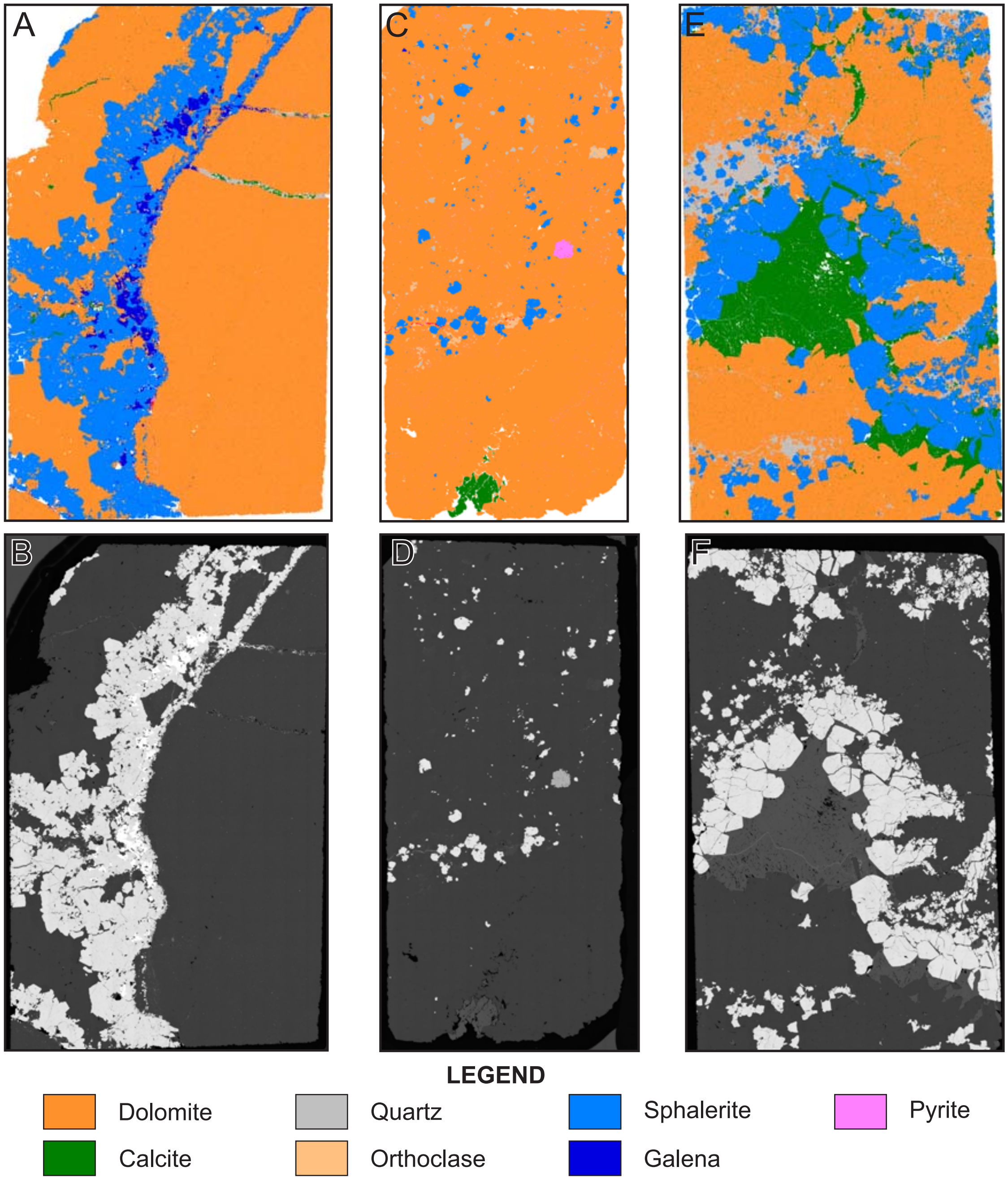

Figure 3. *A) MLA false colour map of a crackle-breccia sample from the Main Zone Trench at the Round Pond Deposit (field of view 39 x 22 mm); B) Backscatter SEM image of A; C) MLA false colour map of mineralized pseudobreccia from the Main Zone Trench at the Round Pond Deposit (field of view 44 x 20 mm); D) Backscatter SEM image of C; E) MLA false colour map of mineralized pseudobreccia from Salmon River #6 (field of view 39 x 22 mm); F) Backscatter SEM image of E.*

with less than 1% yellow sphalerite are stratigraphically below the crackle breccias.

SALMON RIVER #6 PROSPECT

Mineralization at the Salmon River #6 Prospect occurs in the Catoche Formation which, in the area, is composed of dark-brown, thrombolytic, bioturbated, micritic limestones (Knight *et al.*, 1982; Saunders *et al.*, 1992) and locally well-developed pseudobreccias (Knight *et al.*, 1982). Zinc mineralization exposed in trenches (Plate 3A) at Salmon River #6 is sporadic, with only approximately 10% of pseudobreccia samples containing any significant sphalerite. Petrographic analysis has identified three generations of dolomite: 1)

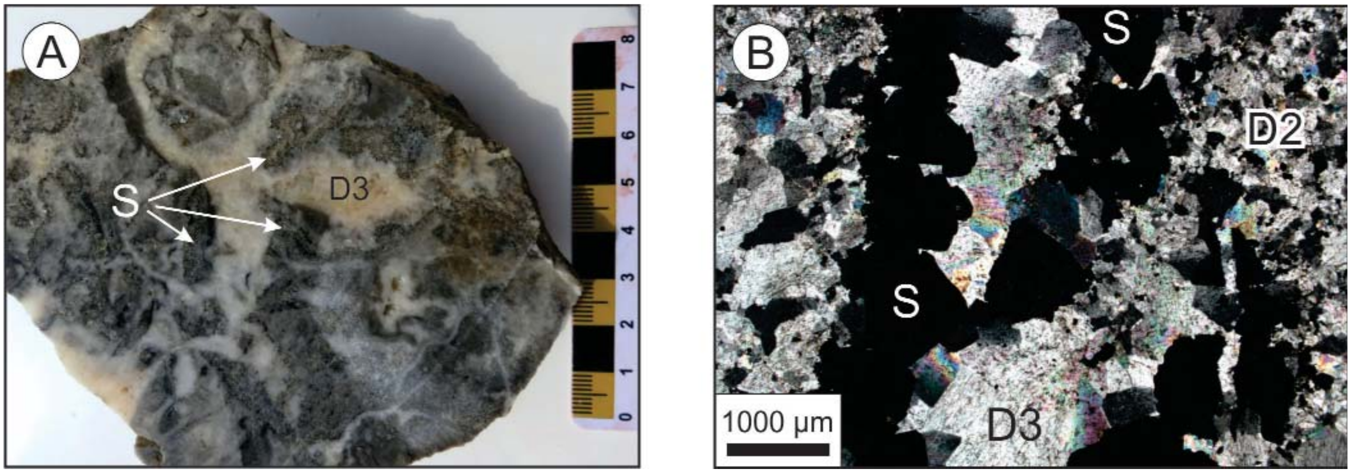

Plate 2. *Selected photographs and photomicrographs from Twin Ponds Prospect. A) Crackle breccia with brown sphalerite and white saddle dolomite filling open space (sample 16JC 018 A01); B) Photomicrograph of euhedral sphalerite and saddle dolomite filling open space in crackle breccia (cross-polarized light, sample 16JC 018 A01). D2 – Medium-grained euhedral dolomite, D3 – Saddle dolomite, S – Sphalerite.*

early fine-grained, dolomitized host-rock clasts, 2) medium-grained, euhedral crystals of dolomite, and 3) a late coarse-grained saddle dolomite. Two generations of void-filling cement have also been recorded, an early black cement consisting of fine-grained K-feldspar, quartz and dolomite (QKD cement) and late-stage white calcite cement. Sphalerite occurs mainly as: 1) relatively coarse-grained, euhedral, and commonly zoned, red crystals along the vug margins in saddle dolomite with the remaining pore space filled by calcite, or 2) as medium-grained yellow anhedral crystals in the QKD cement (Plate 3B, C, D). Rare green sphalerite has also been recorded in some areas. Minor pyrite, hosted in QKD cement, and galena, hosted in late calcite cement, were also observed.

METHODS

Whole-rock samples from outcrop and drillcore were collected from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect during fieldwork in 2016. A total of 21 samples were selected for detailed geochemical and isotopic analyses, ten from the Round Pond Deposit, four from the Twin Ponds Prospect and seven from the Salmon River #6 Prospect. Full analytical details are available in King (2017) and are summarized herein.

All samples selected for lithogeochemical analysis were prepared and analyzed at the GSNL geochemistry laboratory in St. John's. Major-element compositions were analyzed by ICP-OES methods following lithium tetraborate and metaborate fusion, rare-earth elements (REE) and selected trace elements were determined by ICP-MS analysis following an identical sample digestion procedure, whereas the remaining trace elements (Be, Cu, Li, Mn, Ni, Pb, Rb, Sc, Ti, Zn) were analyzed by ICP-OES after total acid digestion. Assays for Zn were determined by ICP-OES after fusion by lithium tetraborate and dilution. The Loss-on-ignition (LOI) was calculated after heating the sample to 1000°C.

Six polished thin sections were selected for detailed geochemical analysis on the Electron Probe Micro Analyser at the Department of Earth Sciences, Memorial University. Thin sections were carbon-coated prior to analysis of zoned sphalerite crystals with a JEOL JXA-8230 microprobe equipped with a W source and 5 WDS spectrometers. Individual crystals were analyzed with a 20nA beam at a 20kV accelerating voltage. Elements reported for each analysis are Zn, S, Fe, Cd, Ga, Mn, Cu, As, Ag and Sb.

Bulk sulphur isotope analysis of sphalerite was carried out at the University of Ottawa. Individual sphalerite crystals were sampled *via* microdrill, weighed into tin capsules with at least twice the sample weight of tungstic oxide for inorganic and organic sulphur, and loaded into a Vario Micro Cube elemental analyzer to be flash combusted at 1800°C. Released gases are carried by helium through the EA to be cleaned, and then separated. The SO_2 gas is carried into the Delta XP isotope ratio mass spectrometer *via* a conflo IV interface for 34S determination. The analytical precision is ± 0.2‰.

Sulphur isotope ratios of pyrite and galena, and lead isotope ratios of galena were analyzed by Secondary Ion Mass Spectrometry (SIMS) at the MAF-IIC Microanalysis Facility, Memorial University. Epoxy mounted Pb and Zn sulphide-bearing rocks were polished and sputter coated

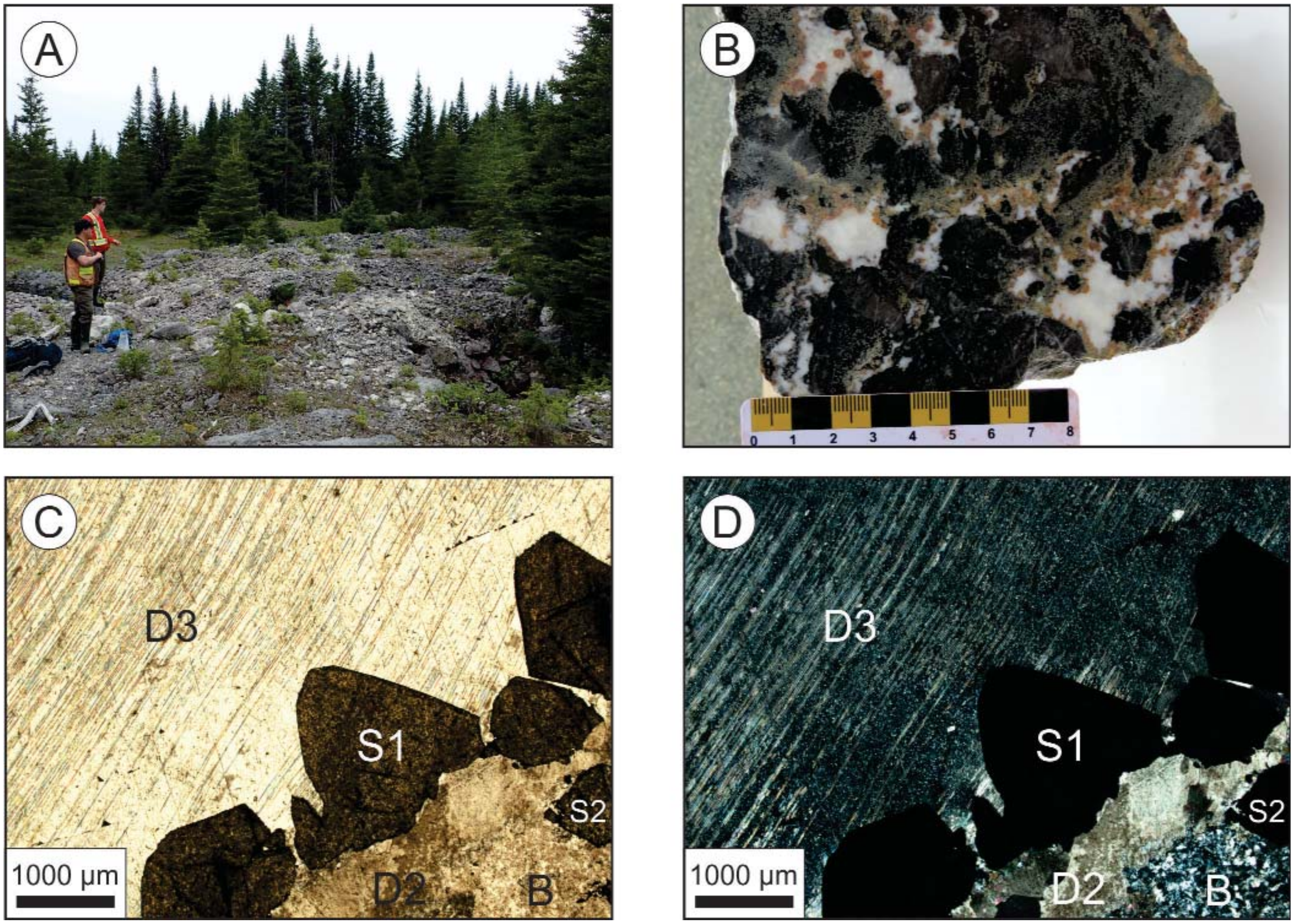

Plate 3. *Selected photographs and photomicrographs from Salmon River #6 Prospect. A) Stripped ground and trenches at Salmon River #6 Prospect; B) Sample 16JC45 A04, with euhedral red sphalerite associated with white dolomite cement and yellow sphalerite in black cement; C) Photomicrograph of euhedral sphalerite lining a vug filled with saddle dolomite (plane-polarized light, sample 16JC045 A01); D) Same view as in C but in cross-polarized light. B – Black cement with quartz, orthoclase and dolomite, D2 – Medium-grained euhedral dolomite, D3 – Saddle dolomite, S1 – Red sphalerite, S2 – Yellow sphalerite.*

with 300Å of Au before analysis by the Cameca IMS 4f Secondary Ion Mass Spectrometer (*see* King, 2017 for full analytical methods).

RESULTS

LITHOGEOCHEMISTRY

Selected major- and minor-element geochemical data for 21 samples from the Round Pond, Twin Ponds and Salmon River #6 are summarized in Tables 1 and 2.

All samples have high MgO and CaO contents (30.4 to 50.0 wt. % combined MgO + CaO). The SiO_2 contents range from 1.3 to 6.7 wt. % at Round Pond and 1.9 to 2.1 wt. % at Twin Ponds. Pseudobreccia samples from Salmon River #6 have higher SiO_2 contents (up to 24.3 wt. %), reflecting the abundance of quartz-rich cement. The Fe_2O_3 contents are low at Round Pond and Salmon River #6 (<1 wt. %), but samples from Twin Ponds have higher Fe_2O_3 contents (1.0 to 3.8 wt. %), which may be related to higher pyrite contents in these samples and/or the presence of ferroan dolomite. All other major-element values are <1 wt. %.

The Zn contents of mineralized crackle-breccia samples at Round Pond range from 2.0 to 24.5 wt. % Zn. A sample of mineralized pseudobreccia from the Main Zone Trench contained 2.1 wt. % Zn, and unmineralized pseudobreccia from the Round Pond Deposit had a Zn content of 0.1 wt. % Zn. Mineralized crackle breccia from the Twin Ponds Prospect have Zn contents of 5.7 to 12.0 wt. %, whereas mineralized pseudobreccia from the Salmon River #6 Prospect have Zn contents of 1.7 to 20.0 wt. %.

Table 1. Whole-rock major-element data from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect

			Zn %	MgO %	CaO %	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	Na_2O %	K_2O %	LOI %
Round	Crackle	Av	10.6	16.7	24.9	3.2	0.5	0.4	0.04	0.22	28.2
Pond	Breccia	Max	24.5	19.9	28.6	6.7	0.9	0.5	0.05	0.46	42.3
	(n = 8)	Min	2.0	12.6	17.7	1.3	0.2	0.3	0.03	0.10	10.6
	Pseudo-	Av	1.1	20.5	28.3	3.0	0.3	0.3	0.04	0.15	41.5
	breccia	Max	2.1	21.1	28.9	4.3	0.3	0.4	0.04	0.16	n/a
	(n = 2)	Min	0.1	19.9	27.7	1.7	0.2	0.3	0.04	0.14	n/a
Twin	Crackle	Av	7.9	18.4	25.2	2.0	0.3	2.0	0.04	0.18	31.1
Ponds	Breccia	Max	12.0	19.6	26.9	2.1	0.3	3.8	0.04	0.19	36.5
	(n = 4)	Min	5.7	17.0	23.2	1.9	0.3	1.0	0.04	0.16	21.4
Salmon	Pseudo-	Av	11.0	14.2	23.8	8.3	0.4	0.4	0.04	0.26	24.8
River #6	breccia	Max	20.0	19.3	28.2	24.3	0.6	0.6	0.05	0.36	42.3
	(n = 7)	Min	1.7	9.1	18.8	3.8	0.2	0.4	0.03	0.14	10.5

Table 2. Selected whole-rock trace-element data from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect

			Ba ppm	Sr ppm	Pb ppm	Cu ppm	Cd ppm	Ga ppm	∑ REE ppm
Round	Crackle	Av	12	45	832	2	249	22	10
Pond	Breccia	Max	20	55	2235	4	405	51	13
	(n = 8)	Min	6	24	34	1	49	4	8
	Pseudo-	Av	10	30	255	2	17	2	38
	breccia	Max	10	31	n/a	2	20	3	66
	(n = 2)	Min	10	30	n/a	2	15	2	10
Twin	Crackle	Av	9	26	103	5	146	16	15
Ponds	Breccia	Max	112	28	183	9	202	24	17
	(n = 4)	Min	8	25	31	2	112	9	10
Salmon	Pseudo-	Av	22	75	18	12	273	3	21
River #6	breccia	Max	34	171	65	27	535	4	37
	(n = 7)	Min	13	38	3	2	32	2	10

The Pb contents range from 34 to 2235 ppm at Round Pond, and 31 to 183 ppm at Twin Ponds. Samples from the Salmon River #6 Prospect generally have lower Pb contents (3 to 65 ppm; Figure 4). The Cu contents are generally low (<10 ppm), but some Salmon River #6 samples have Cu contents >10 ppm. The Ga content of samples from Salmon River #6 (average 3 ppm) however, is lower than crackle-breccia samples from Round Pond and Twin Ponds (average 22 and 16 ppm, respectively).

Other trace-element contents are generally low (<10 ppm), commonly below their detection limits. Large ion lithophile elements (LILE) contents are relatively low, with Ba contents of 6 to 34 ppm and Sr contents of 24 to 171 ppm. With the exception of a single sample of unmineralized pseudobreccia, total REE contents (∑ REE) of samples from Round Pond and Twin Ponds are <17 ppm, with samples from Salmon River having higher ∑ REE contents (10 to 37 ppm).

ELECTRON PROBE MICRO ANALYSIS (EPMA)

The EPMA traverses across sphalerite crystals were conducted on six samples; two from Round Pond, one from Twin Ponds and three from Salmon River #6. In total, 11 traverses were completed, with 283 individual spot analyses.

The Zn and S are the dominant elements determined in each analysis (98.27 to 99.95%), and the dominant elements detected at trace concentrations are Fe and Cd. The Fe contents range from 581 to 2470 ppm in Round Pond samples, 426 to 12781 ppm at Twin Ponds, and 1389 to 9263 ppm at Salmon River #6 Prospect. The Cd contents range from 105 to 3226 ppm in Round Pond samples, 76 to 5834 ppm at Twin Ponds, and 761 to 7774 ppm at Salmon River #6 Prospect. Analyses from Round Pond do not show any systematic variation in Fe and Cd contents (Figure 5A). In contrast, analyses from Twin Ponds indicate that Fe and Cd con-

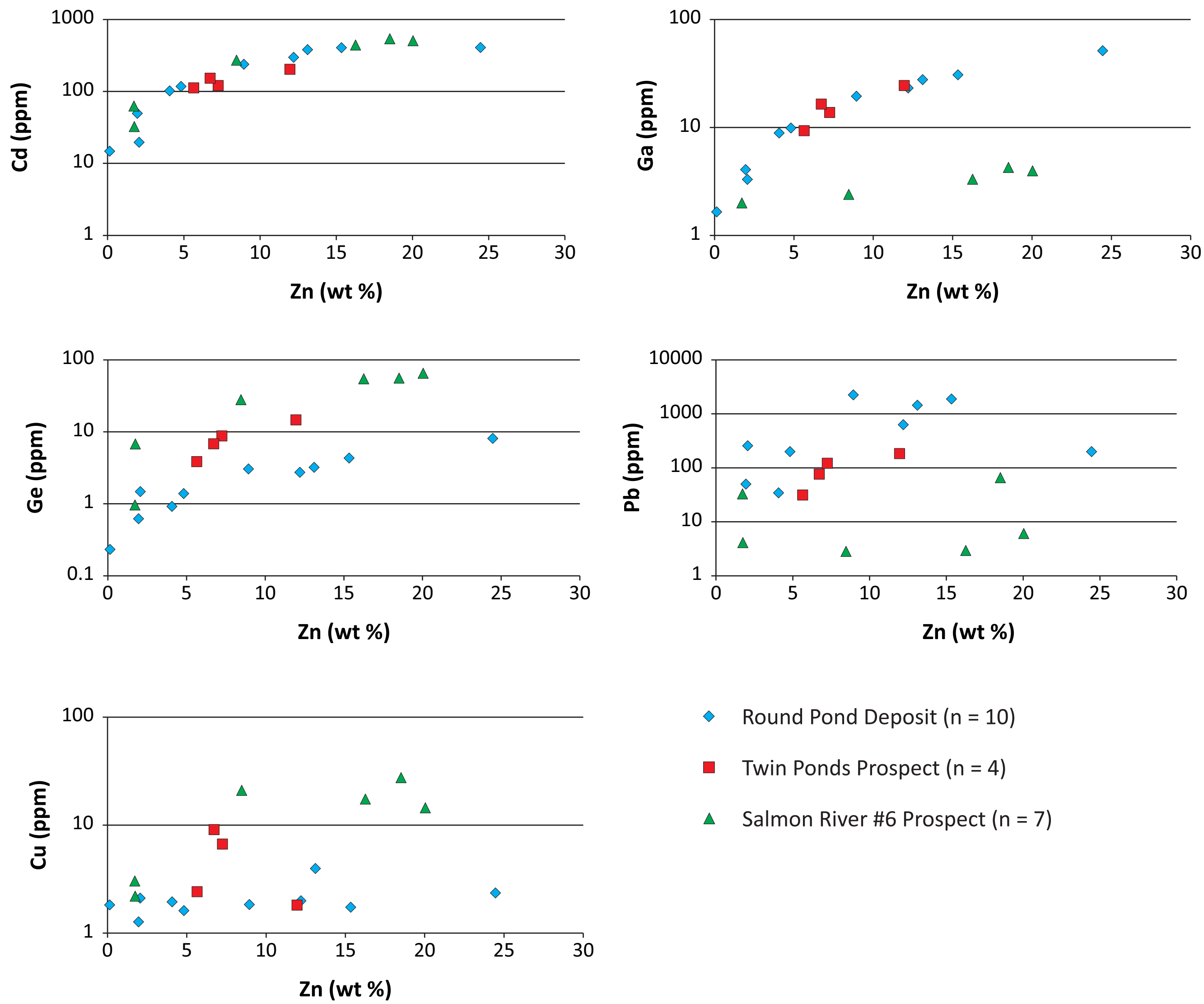

Figure 4. *Bivariate plots of selected metals* vs. *Zn from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect. Data from whole-rock geochemistry;* see *text for discussion.*

tents are negatively correlated (Figure 5B), whereas those from Salmon River #6 Prospect show a positive correlation between Fe and Cd (Figure 5C). The relative proportions of Fe and Cd in sphalerite are responsible for the zonation seen in petrographic analysis of sphalerite crystals (King, 2017). With the exception of Cu contents at Salmon River #6 Prospect (51 to 993 ppm), all other trace-element concentrations are low (generally <150 ppm) and no correlations were observed between these elements.

SULPHUR ISOTOPES

Bulk sulphur isotope data from sphalerite, and SIMS spot analyses data from galena and pyrite are summarized in Table 3.

Sulphur isotope data were obtained from sphalerite in four samples from the Round Pond Deposit and three samples from the Salmon River #6 Prospect. The $\delta^{34}S$ ratios of Round Pond Deposit sphalerite range from +14.2‰ to +20.9‰ (Figure 6). The $\delta^{34}S$ ratios for green sphalerite at Salmon River #6 has a value of 0.0‰, whereas red and yellow sphalerite were +15.7‰ and +21.8‰, respectively (Figure 6).

The SIMS analyses of galena and pyrite have wide ranges in $\delta^{34}S$ values. Galena in samples from the Round Pond Deposit have $\delta^{34}S$ values ranging from +13.0‰ to +30.4‰ (Figure 6). Pyrite from Salmon River #6 has $\delta^{34}S$ values ranging from +21.0‰ to +25.7‰, whereas pyrite at Twin Ponds has $\delta^{34}S$ values ranging from +0.1‰ to +6.5‰.

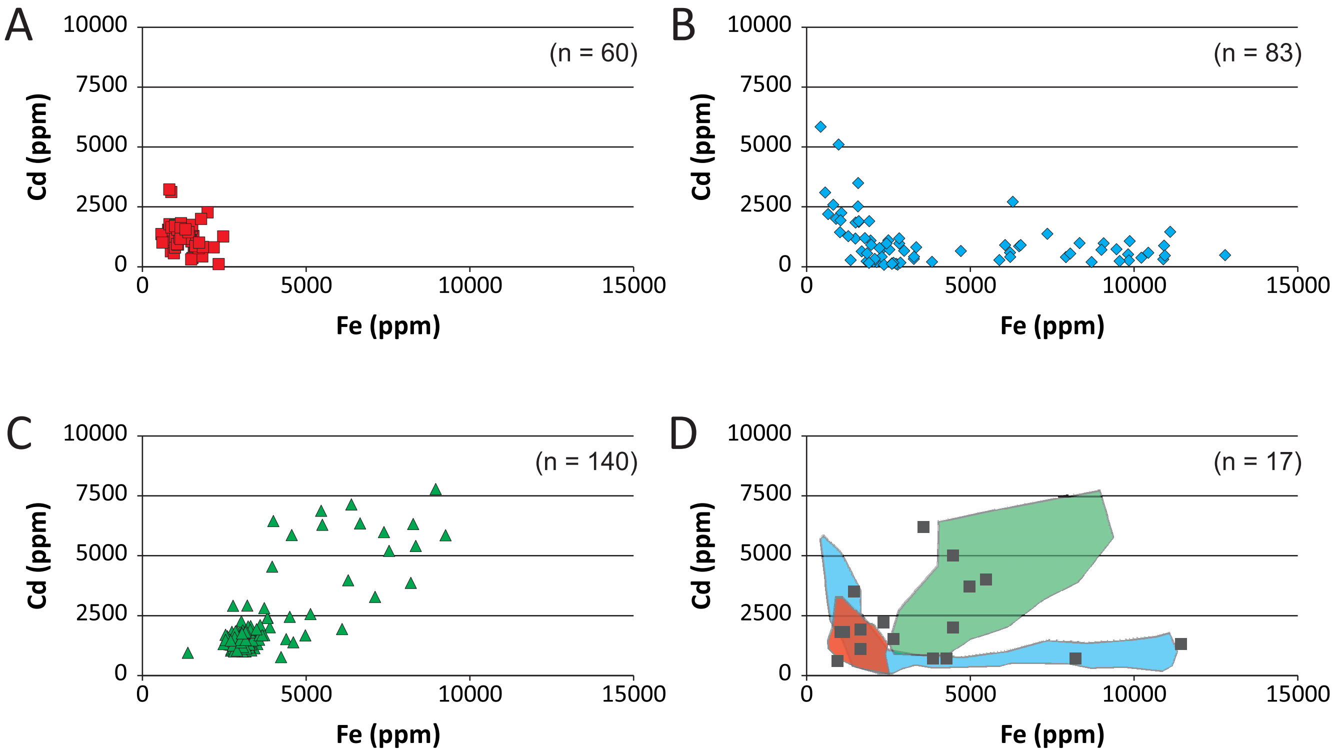

Figure 5. *Bivariate plots of Cd* vs. *Fe from EPMA of sphalerite crystals. A) Data from Round Pond Deposit; B) Data from Twin Ponds Prospect; C) Data from Salmon River #6 Prospect; D) Data from Daniel's Harbour Deposit (from Lane, 1990), with shaded field showing results from Round Pond Deposit (red), Twin Ponds Prospect (blue) and Salmon River #6 Prospect (green).* See *text for discussion.*

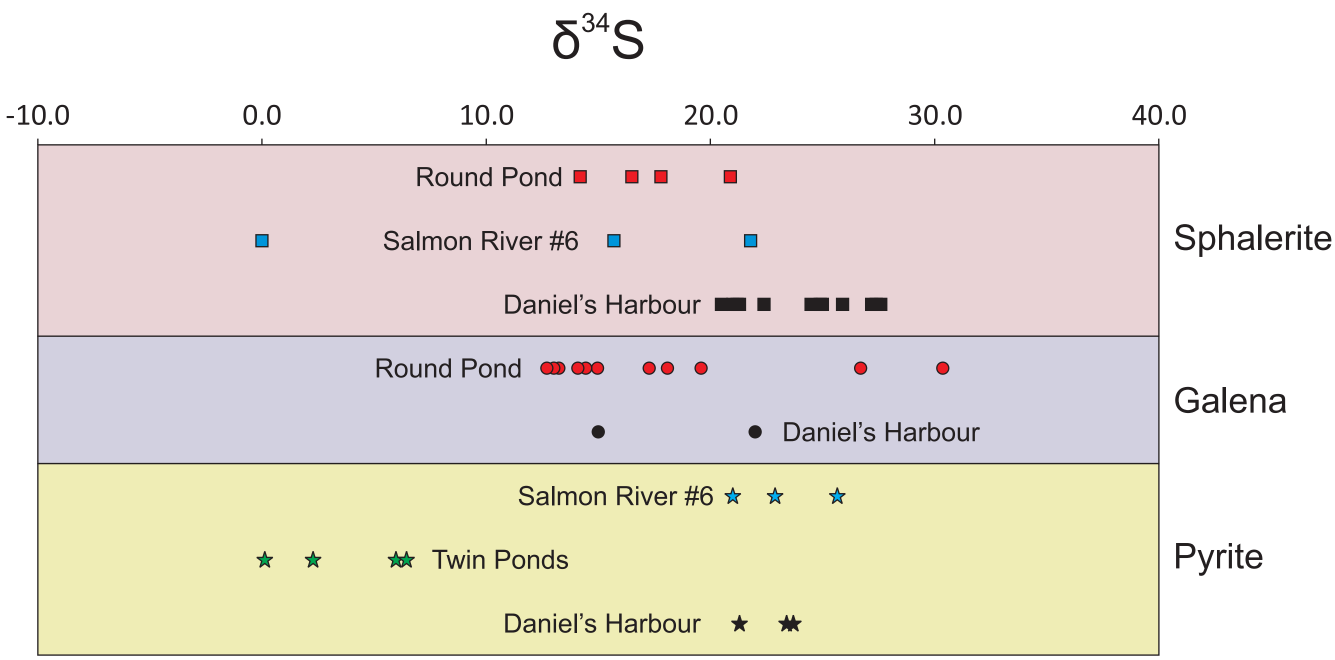

Figure 6. *Diagram illustrating $\delta^{34}S$ values of sulphides (sphalerite, galena, and pyrite) from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect (*this study*) and from the Daniel's Harbour Deposit (from Lane, 1990).*

Table 3. Sulphur isotope values for sphalerite, galena and pyrite from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect

Deposit	Sample	Host Mineral	Method	$\delta^{34}S$
Round Pond	16JC 026 A02	Sphalerite	Bulk	14.2
				17.8
	16JC 027 A02			16.5
	16JC 029 A01			20.9
	16JC 026 A03	Galena	SIMS	30.4
				26.7
				12.7
				19.6
	16JC 027 A01			13
				18
				13.2
				15
				14.3
				14.1
				18.1
				14.4
				17.3
Twin Ponds	16JC 017 A03	Pyrite	SIMS	0.1
				2.3
				6
				6.5
Salmon River #6	16JC 043 A01	Sphalerite	Bulk	15.7
	16JC 044 A01			0
	16JC 045 A02			21.8
	16JC 045 A01	Pyrite	SIMS	22.9
				21
				25.7

Table 4. Pb-isotope ratios from the Round Pond Deposit

Deposit	Sample	Spot	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}/Pb/^{204}Pb$
Round Pond	16JC 026 A03	1a	18.245	15.765	38.870
		1b	18.266	15.745	38.711
		1c	18.222	15.728	38.609
		2a	18.191	15.638	38.434
		2b	18.178	15.652	38.449
		2c	18.249	15.730	38.627
	16JC 027 A01	1a	18.195	15.796	39.156
		1b	18.209	15.759	38.975
		1c	18.209	15.654	38.304
		1d	18.217	15.661	38.367
		1e	18.140	15.660	38.436
		1f	18.240	15.688	38.519
		2a	18.290	15.709	38.540
		2b	18.214	15.688	38.542
		2c	18.250	15.689	38.466
		2d	18.244	15.746	38.766
		2e	18.255	15.872	39.322
		2f	18.268	15.783	39.011

LEAD ISOTOPES

The Pb isotope data obtained by SIMS analysis of galena are summarized in Table 4, with plots of $^{206}Pb/^{204}Pb$ *vs.* $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ *vs.* $^{208}Pb/^{204}Pb$ displayed in Figure 7. The Pb isotope data were collected from four galena crystals (2 grains in 2 different samples) from the Round Pond Deposit, which yielded Pb isotope ranges of $^{206}Pb/^{204}Pb$ = 18.1398 to 18.2900, $^{207}Pb/^{204}Pb$ = 15.6381 to 15.8720, and $^{208}Pb/^{204}Pb$ = 38.3039 to 39.3215. Compared to the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios, which display significant variation in their respective ranges, there is little variation in the $^{206}Pb/^{204}Pb$ ratios.

DISCUSSION

GEOCHEMISTRY OF Zn OCCURRENCES

The major-element contents obtained from whole-rock geochemical analysis reflect the relatively simple mineralogy of the samples, dominated by dolomite ($CaMg(CO_3)_2$) and sphalerite (ZnS), with lesser calcite ($CaCO_3$), quartz (SiO_2), orthoclase ($KAlSi_3O_8$), pyrite (FeS_2) and galena (PbS). Trace-element contents are generally low (<10 ppm), with many elements below their detection limit, which makes interpretation of the data difficult. However, there are some systematic variations in metal associations recorded between deposits.

Bivariate plots of selected metals *vs.* Zn contents are shown in Figure 4, and the correlation coefficients (R^2) between these metals and Zn contents are presented in Table 5. These data show that there is an excellent correlation between Zn and Cd contents in all deposits, with R^2 values of >0.8. Similarly, Ga shows a strong correlation with Zn content (R^2 >0.89), although overall Ga content is lower in samples from the Salmon River #6 Prospect. The Ge contents also show a strong linear relationship, and if a single anomalously high Ge value from Salmon River #6 is removed, all datasets have R^2 values >0.93. Samples from Round Pond and Twin Ponds have higher Pb and lower Cu contents compared to samples from Salmon River #6 Prospect (Figure 4), but there is a much weaker correlation with Zn content; consistent with the crystallization of discreet Pb and Cu sulphides. Overall, these data suggest differneces in the metal contents of the mineralizing fluids between these deposits, with Round Pond and Twin Ponds enriched in Ga and Pb, and Salmon River #6 Prospect enriched in Cu and Ge.

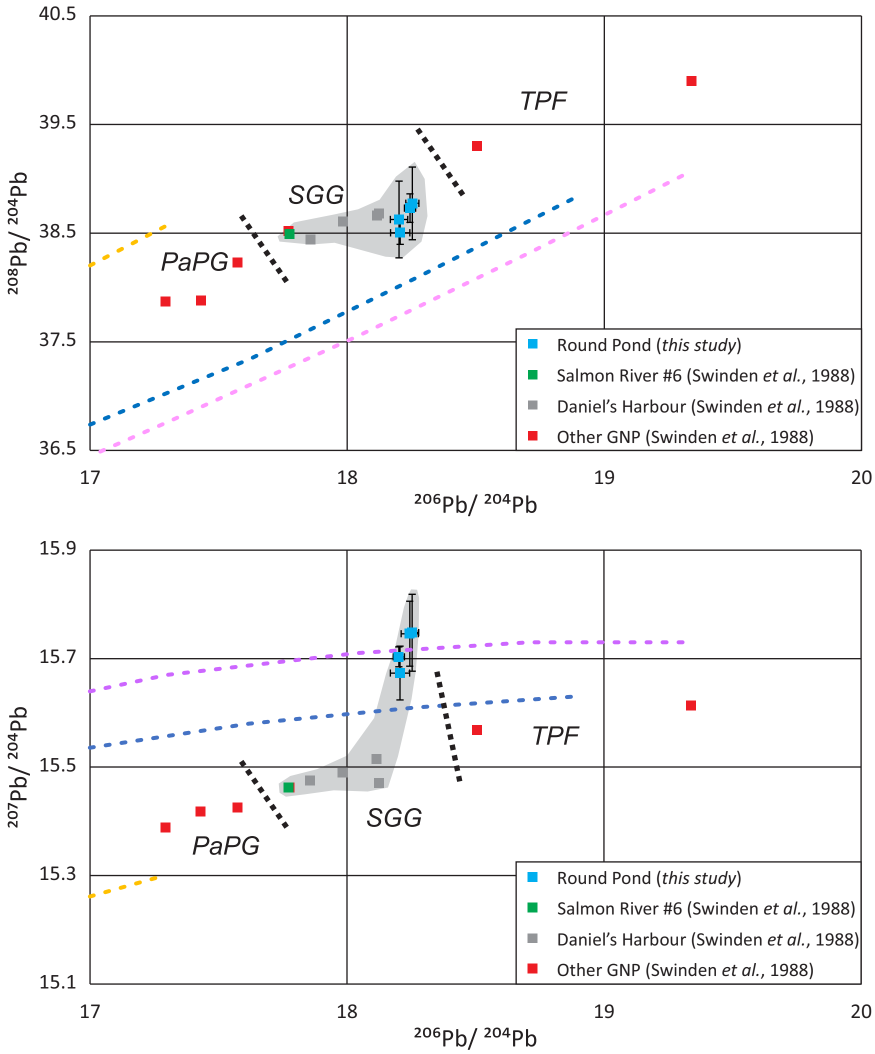

Figure 7. *Lead-isotope data showing obtained values from galena at the Round Pond Deposit, compared with data from other Zn–Pb occurrences on the Great Northern Peninsula (after Swinden* et al*., 1988). Blue square represents median value from single galena grain, error bars represent standard deviation. Stippled lines represent stratigraphic divisions from Swinden* et al. *(1988), shaded area represents field of Pb-isotope values for MVT-type occurrences in St. George Group carbonates (*see *text for discussion). Zartman and Doe (1981) model growth curves shown for reference. PaPG – Port au Port Group, SGG – St. George Group, TPF – Table Point Formation.*

The trace-element composition of sphalerite has been shown to be related to crystallization temperature, metal source, and the relative input of deep hydrothermal fluids and basinal brines (Cook *et al.*, 2009; Pfaff *et al.*, 2011; Gagnevin *et al.*, 2014; Frenzel *et al.*, 2016). Trace elements can be incorporated into the sphalerite crystal structure either as solid solutions (*e.g.*, Fe, Cd, Mn, Ga) or as micro inclusions (<5 µm) in sphalerite grains (*e.g.*, Cu, Ge, Sb, Ag) (Cook *et al.*, 2009). The EPMA of sphalerite from all studied locations shows that Fe and Cd are the main trace elements, with significant Cu (51 to 993 ppm) recorded at Salmon River #6. All other trace-element contents are low, with only sporadic values above detection limits. Although Ga contents are below the EPMA detection limit (84 ppm), whole-rock geochemical data indicate that Cd and Ga correlate with Zn contents (Figure 4; Table 5), consistent with incorporation of these elements into sphalerite *via* solid solution. The Fe and Mn may have also been incorporated *via* solid solution, although the presence of other Fe-bearing minerals (*e.g.*, pyrite, ankerite) makes direct correlations between Fe and Zn contents impossible. Although samples from Salmon River #6 have relatively high Cu contents, Cu is not readily incorporated into the crystal structure of sphalerite and it is likely due to 'chalcopyrite disease', where sub-5µm blebs of chalcopyrite exsolve as the sphalerite cools (Cook *et al.*, 2009). Other elevated trace-element contents (Sb up to 1454 ppm, Ag up to 390 ppm, As up to 1140 ppm) are likely due to the presence of micro inclusions in the sphalerite.

The EPMA traverses across individual sphalerite grains show that Fe and Cd contents vary between occurrences on the GNP (Figures 5 and 8). At Twin Ponds, Cd and Fe contents are inversely proportional, and have highly variable Fe/Cd ratios (Figure 8). Dark zones in sphalerite are characterized by elevated Fe and depleted Cd contents (Figure 9). The Cd contents in sphalerite are thought to be independent of fluid temperature (Frenzel *et al.*, 2016), and therefore these variations are variable proportions of two end-member fluids, one enriched in Cd and a second enriched in Fe. Sphalerite from Round Pond is characterized by lower, and less variable, Fe/Cd ratios. The data plot along a similar trend to data from Twin Ponds (Figure 8), and some Fe enrichment and Cd depletion are associated with colour zones in sphalerite (Figure 9). Gagnevin *et al.* (2014) reported similar results from zoned sphalerite from the Irish-type carbonate-hosted ore bodies, where sphalerite precipitation is due to the mixing of metal-bearing fluids with elevated Cd and sulphur-bearing fluids elevated in Fe. A similar mecha-

Table 5. Correlation coefficient (R^2) between Zn contents and selected metal contents from the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect. Values calculated from whole-rock geochemical data

	Round Pond Zn	Twin Ponds Zn	Salmon River #6 Zn
Cd	0.87	0.85	0.84
Cu	0.16	0.20	0.48
Pb	0.09	0.87	0.04
Ga	1.00	0.89	0.89
Ge	0.94	0.94	0.99*

* correlation coefficient excludes single anomalous value

nism is proposed for the Twin Ponds and Round Pond occurrences.

At Salmon River #6, EPMA of sphalerite shows a broadly linear relationship between Fe and Cd contents (R^2 = 0.65), having a much more restricted range of Fe/Cd values (Figure 8), and no variation in Fe and Cd ratios associated with colour zones in sphalerite (Figure 9). The variations in Fe and Cd contents observed in individual sphalerite crystals during traverses (Figure 9) indicate the presence of two-distinct fluids, which is consistent with previous fluid inclusion analysis by Saunders *et al.* (1992) at Salmon River #6 Prospect. However, the contrasts between Fe/Cd ratios in sphalerite from Salmon River #6 and from Round Pond and Twin Ponds support evidence from whole-rock geochemistry that the metal content of mineralizing fluids was different.

METAL SOURCE

To determine the source of metal-bearing fluids on the GNP, the Pb-isotope composition of galena from the Round Pond Deposit (*this study*) has been compared with previous data from the Daniel's Harbour Deposit, Salmon River #6 Prospect and a number of other occurrences on the GNP (data from Swinden *et al.*, 1988). These data are plotted on Figure 7, where plots of $^{208}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ show that the data from Round Pond lie on the linear trend previously defined by Swinden *et al.* (1988). In contrast, samples from Round Pond are significantly enriched in ^{207}Pb, and plot away from the linear trend defined on $^{207}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ diagrams by Swinden *et al.* (1988). This may be related to the differing methods between this study (SIMS analysis) and Swinden *et al.* (1988) (TIMS analysis), or could reflect a more radiogenic Pb source at Round Pond (U-rich Precambrian granitic basement or basement-derived sediment source).

Swinden *et al.* (1988) concluded that the linear trends observed on $^{208}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ diagrams represented mixing between two distinct Pb sources, with Pb at the non-radiogenic end sourced in the Th-rich high-grade metamorphic Grenvillian basement, and the more radiogenic Pb sourced in the overlying sedimentary rocks. This is supported by the relationship between Pb-isotope composition and stratigraphic height (a proxy for distance from the basement), with the most radiogenic Pb values in samples hosted in rocks of the Table Point Formation and the least radiogenic Pb values recorded in the Cambrian Port au Port Group (Figure 7). However, some occurrences included in this trend are geologically dis-

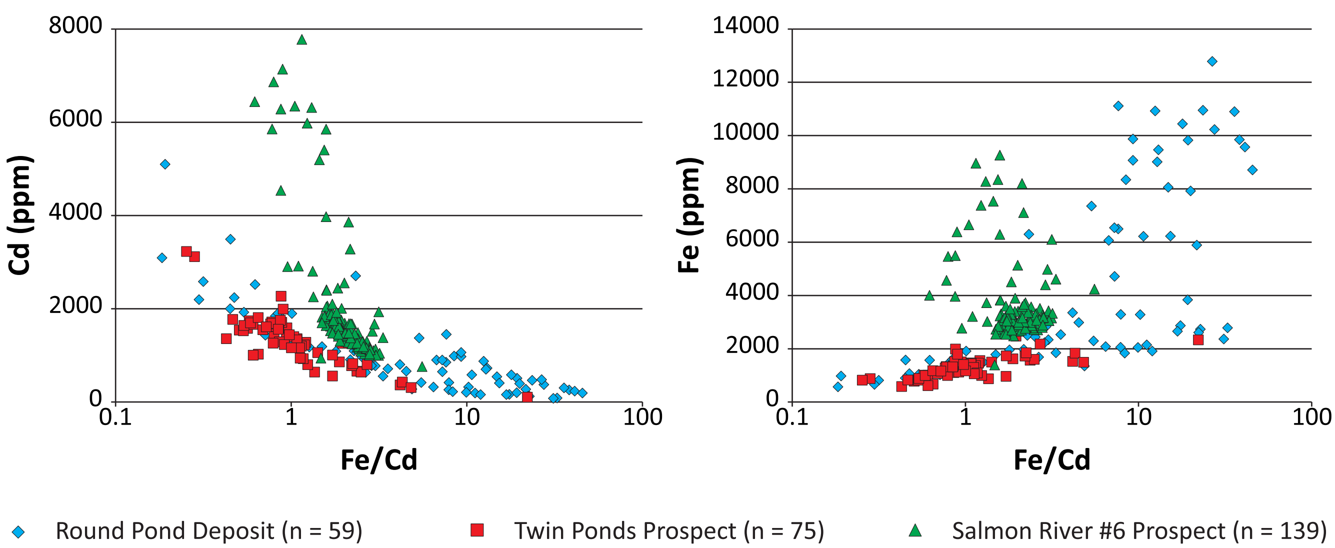

Figure 8. *Bivariate plots of Fe and Cd contents* vs. *Fe/CD ratios, showing variations between occurrences (data from EPMA of sphalerite crystals).* See *text for discussion.*

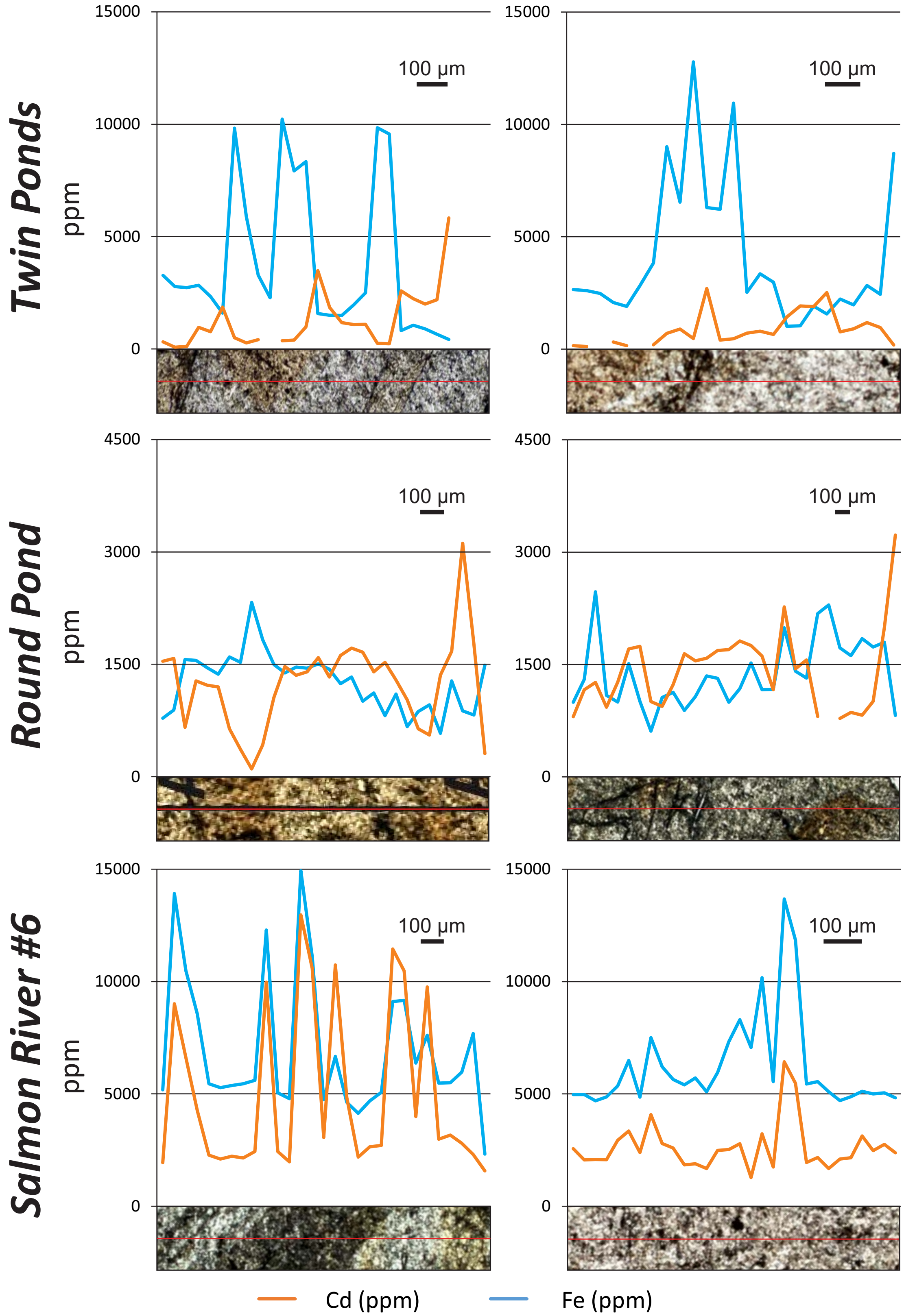

Figure 9. *EPMA traverses across sphalerite crystals at the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect. The Fe and Cd concentrations across the crystals displayed, show variations in trace-element composition related to colour zones in the sphalerite.*

tinct from the MVT-type deposits at Daniel's Harbour, Round Pond and Salmon River #6 (*e.g.*, Pikes Feeder Pond, Eddies Cove; Saunders *et al.*, 1992), and it is unclear if these occurrences formed from the same mineralizing fluids (and associated metal sources). If only data from MVT-type occurrences are included, the Pb isotope ratios form a much steeper trend on the $^{207}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ diagram compared to the $^{208}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ (Figure 7), and this trend is unrelated to the stratigraphic height of the occurrences. Therefore, the Pb-isotopic signature may represent mixing between a non-radiogenic end member and a radiogenic end member enriched in U (^{207}Pb), but relatively depleted in Th (^{208}Pb).

Alternatively, the complex tectonic history of western Newfoundland could have led to the creation of multiple fluid pathways capable of leaching Pb and other metals from the basement rocks. Given the heterogeneity of the Grenvillian basement rocks of the Long Range Inlier (Owens, 1991), it is possible that the non-radiogenic Pb could have been derived from multiple sources. Although no data are available on the Pb-isotopic signature of the Grenvillian basement rocks in western Newfoundland, the variations in metal contents between Round Pond and Salmon River #6 support the hypothesis that the mineralizing fluids leached their metals from different crustal sources. Also, it must be considered that samples are taken from only one location in a larger mineralizing system, and isotopic signatures and metal contents may vary greatly within individual deposits. Therefore, more research is required to determine the source of the distinct Pb-isotopic signatures of these occurrences.

SULPHUR SOURCE

A number of models have been proposed for ore precipitation in MVT deposits (Leach *et al.*, 2005), including models where sulphur is transported (either as sulphate or reduced sulphate) in the same fluid as the metals (single-fluid model), or models invoking mixing of sulphate-poor, metal-bearing brines having a sulphur source at the depositional site (fluid-mixing model). The single-fluid model is considered unlikely, as the transport of significant quantities of sulphur in a metal-bearing fluid would require a highly oxidizing fluid with low pH (Wilkinson, 2014). Therefore, ore precipitation on the GNP is interpreted to be related to fluid-mixing, with basement derived, metal-bearing fluids mixing with sulphur derived from crustal sources.

Crustal sources of sulphur can include sulphate-bearing evaporates, diagenetic sulphides, H_2S in hydrocarbon reservoir fluids, sulphur-bearing organic matter and connate seawater trapped in pore spaces (Leach *et al.*, 2005). There is little evidence for evaporate deposition in the St. George Group carbonates, except for minor silicified and dolomitized pseudomorphs after anhydrite (Knight and James, 1987); therefore, it is unlikely that sulphate-bearing evaporates were a significant source of sulphur. Similarly, diagenetic pyrite is rare in the St. George Group carbonates and is not considered a likely source of sulphur. The H_2S associated with petroleum reservoirs in the host dolomites is considered a possible sulphur source, as the carbonates of the St. George Group are known to be potential hydrocarbon reservoirs (Cooper *et al.*, 2001). However, the carbonate rocks north of Daniel's Harbour are thermally overmature (Williams *et al.*, 1998), and when combined with the lack of evidence for oil shows in these rocks, it is unlikely that hydrocarbons were a significant source of sulphur.

Previous exploration at Round Pond had noted the association between sulphide mineralization and bituminous zones in the host carbonates (Born, 1983), and therefore, organic matter is a possible sulphur source in this location. However, this bituminous residue may also be a product of sulphur reduction during precipitation of sulphides (*see* below). The incorporation of sulphur *via* sulphidic brines is also considered a viable sulphur source on the GNP. Sulphate derived from Paleozoic seawater trapped in pore spaces during diagenesis and released from sedimentary strata during deformation may have provided a sulphur source. Precipitation of sulphide would have occurred when these brines mixed with metal-bearing fluids.

The reduction of crustal sulphate and subsequent precipitation of ore sulphides during the formation of MVT deposits can be controlled by one of two main processes (Thom and Anderson, 2008); bacterial action at temperatures above 80°C (Bacterial Sulphate Reduction = BSR), or abiotic processes at temperatures in excess of 100°C (Thermochemical Sulphate Reduction = TSR). The sulphur isotopic compositions of sulphides formed by these processes are distinct (Machel, 2001), with BSR associated sulphides characterized by negative $\delta^{34}S$ ratios, and sulphides formed by TSR enriched in ^{34}S ($\delta^{34}S$ >5‰). Sphalerite, galena and pyrite at the Round Pond and Salmon River #6 occurrences are generally enriched in ^{34}S (Figures 6 and 10), and have $\delta^{34}S$ values from 12.7 to 30.4‰ at the Round Pond Deposit, and from 15.7 to 25.7‰ at Salmon River #6 (with the exception of a single green sphalerite sample that yields $\delta^{34}S$ value of 0.0‰). This indicates that TSR is the main sulphur-reducing process at Round Pond and Salmon River #6, and the similarity between the $\delta^{34}S$ values from these occurrences and those previous reported from the Daniel's Harbour Deposit (Figures 6 and 10; Lane, 1990) suggests that TSR was a common process throughout the GNP. This interpretation is consistent with minimum formation temperatures obtained from previous fluid inclusion studies, which indicate that these occurrences formed at tempera-

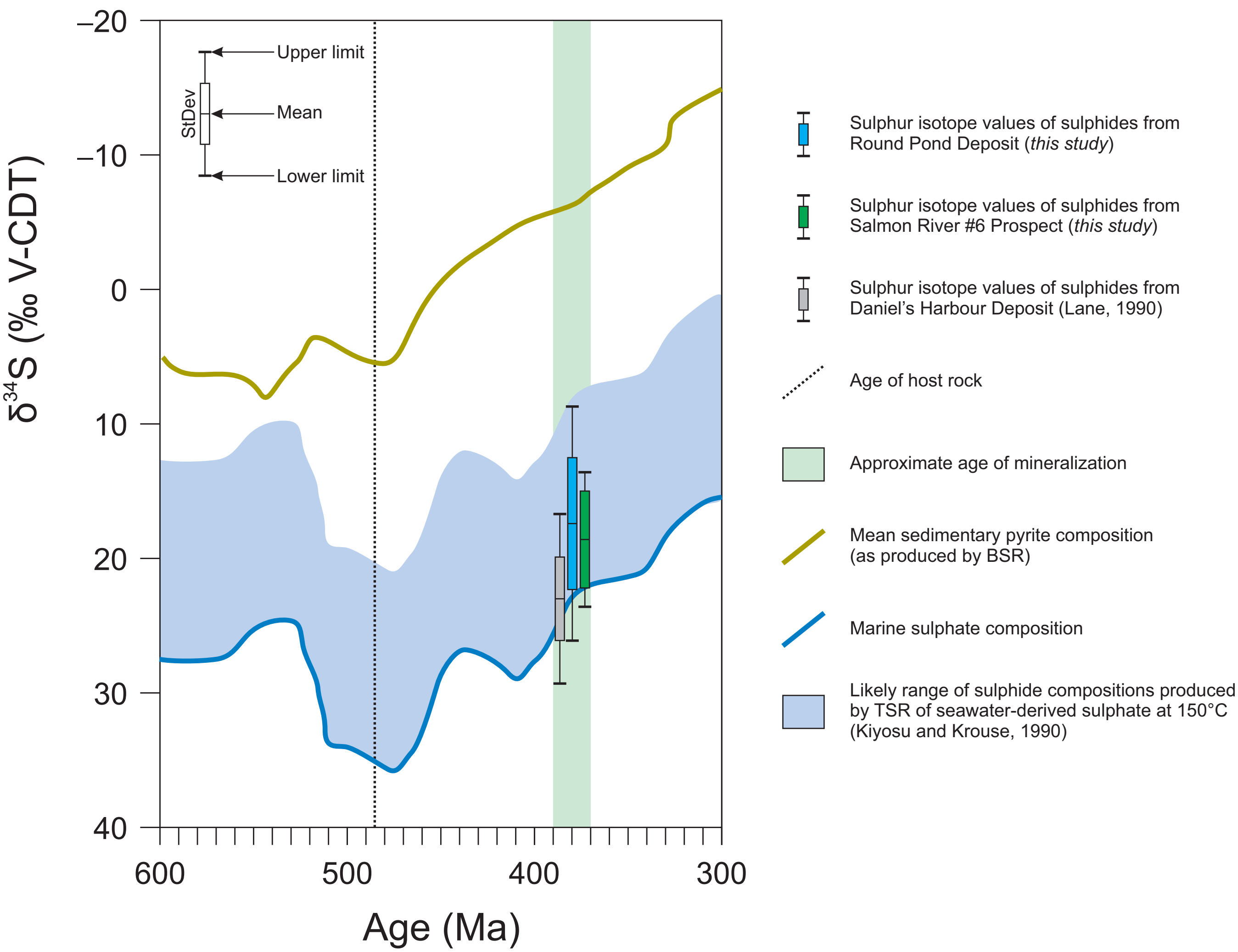

Figure 10. *Median and range of $\delta^{34}S$ values of sulphides (sphalerite, galena and pyrite) from the Round Pond Deposit (*this study*), Salmon River #6 Prospect (*this study*) and Daniel's Harbour Deposit (data from Lane, 1990), plotted against the age of the host carbonates and the inferred mineralization age from paleomagnetic data (Pan and Symons, 1993). Sulphur isotope curves and likely range of sulphide compositions produced by TSR adapted from Wilkinson (2014), after Kiyosu and Krouse (1990) and Farquhar* et al. *(2010).* See *text for discussion.*

tures in excess of 100°C (Lane, 1990; Saunders *et al.*, 1992), much higher than is feasible for BSR (Machel, 2001). In addition, the presence of bitumen in association with zinc mineralization at Round Pond, and the recognition of CO_2-bearing fluid inclusions in sphalerite from Round Pond (Saunders *et al.*, 1992), support the theory that TSR is the dominant process responsible for sulphide precipitation, as these are known to be products of TSR reactions (Machel, 2001). Comparisons between the ^{34}S composition of sulphides on the GNP and the likely range of sulphide compositions produced by TSR of seawater-derived sulphate at 150°C (adapted from Wilkinson, 2014) are shown in Figure 10, being consistent with the production of sulphides by TSR of Paleozoic seawater sulphate.

The sulphur isotope data from pyrite at the Twin Ponds Prospect are different from the other occurrences described in this study, with much lower ^{34}S ratios (0.0 to 6.5‰; Figure 6). This indicates that these sulphides incorporated a proportion of sulphur derived by BSR, with pyrite mainly hosted in dolomite clasts and predating the main mineralization event. Fluid inclusion data from Saunders *et al.* (1992), however, show minimum formation temperatures of >94°C, indicating that BSR was not responsible for the main sphalerite mineralization. Although no data are available for the main stage sphalerite mineralization, it is likely that TSR is the dominant sulphur-reducing process at this occurrence as well.

GENETIC MODEL

A simplified genetic model for the formation of MVT-type occurrences on the GNP is shown in Figure 11, based on the geological and geochemical data presented above. The St. George Group carbonate platform rocks were deformed during the Taconic Orogeny (Waldron and Stockmal, 1994; Stockmal *et al.*, 1998; van Staal and Barr, 2012), resulting in the formation of orogen parallel normal and thrust faults (Waldron and Stockmal, 1994; Stockmal *et al.*, 1998). During this deformation, sulphate-bearing connate water in sedimentary strata would have been expelled and migrated through the carbonate rocks, and may have been responsible for secondary hydrothermal dolomitization and porosity development in these units (Conliffe *et al.*, 2012). This porosity would have enhanced later fluid flow, and provided a crustal reservoir for these sulphate-rich fluids.

A second phase of deformation during the Acadian Orogeny led to the formation of deep-seated, thick-skinned thrust faults that penetrated the Grenvillian basement rocks (Waldron and Stockmal, 1994; Stockmal *et al.*, 1998). Paleomagnetic dating of the Daniel's Harbour Deposit suggests a Middle Devonian mineralization age (Pan and Symons, 1993), and it is likely that mineralization is associated with hydrothermal fluid flow during the Acadian Orogeny. Hydrothermal fluids passing through these faults leached metals as they passed through the basement rocks (plus sedimentary strata), and would have entered the St. George Group carbonates through the deep-seated thrust faults and networks of normal and thrust faults developed during Taconic deformation (Figure 11). In the Hare Bay area, these include the Ten Mile Fault Zone, which is a braided system of northeast- and north-trending faults cutting the carbonate sequence (Knight, 1986). These fluids would have moved laterally through porous dolomites, possibly aided by overlying and underlying dolomite aquitards with lower porosity and permeability (Figure 11). Mixing of these metal-bearing fluids with sulphate-rich fluids in the porous dolomites (Figure 11) would have resulted in the precipitation of sulphide minerals (sphalerite, galena, pyrite) *via* TSR at elevated temperatures (>100°C).

This model is supported by geochemical data (presence of distinct Fe- and Cd-rich fluids), Pb isotope data (metals sourced from underlying basement and sedimentary rocks) and S isotope data (TSR of Paleozoic seawater sulphate). In addition, fluid inclusion data from the Salmon River #6 Prospect support the mixing between high-temperature hydrothermal fluids and lower temperature brines (Saunders *et al.*, 1992). Therefore, these occurrences can be classified as syn-collisional MVT deposits, similar to deposits in Northern Arkansas (Bradley and Leach, 2003), with Acadian mineralization facilitated by an early stage of deformation during the Taconic.

EXPLORATION IMPLICATIONS

This study has shown that the Zn-occurrences at Round Pond, Twin Ponds and Salmon River #6 are typical of syn-collisional MVT deposits, similar in geology and geochemistry to the Daniel's Harbour Deposit. In addition, the well-developed pseudobreccias, with numerous sphalerite showings, over a strike length of more than 60 km from Salmon River to North Boat Harbour highlight the exploration potential. The genetic model outlined above aids future exploration in this area, as information on the type and nature of mineralization can help better target and rank prospects. In particular, this information is useful in locating blind orebodies that do not crop out at the surface. Future exploration should pay close attention to the stratigraphy of the St. George Group carbonates, with the aim of identifying porous dolomite horizons that may host economic ore deposits. Detailed structural studies, including 2-D and 3-D seismic surveys, may be used to map subsurface structures and help identify suitable pathways for mineralizing fluids. Detailed till geochemical surveys may help identify new occurrences on the GNP, and using the data above, the geochemical analysis of sulphides in tills (*e.g.*, sphalerite, galena) may link these soil anomalies to individual deposits or deposit types.

FUTURE WORK

Planned future work on MVT-type Zn occurrences on the GNP include detailed fluid inclusion studies to determine the nature and temperature of mineralizing fluids, and to provide more evidence for fluid mixing during ore deposition. In addition, detailed *in-situ* geochemical analysis of sphalerite using LA-ICP-MS techniques is required, as most trace-element contents were below the detection limit during EPMA. Frenzel *et al.* (2016) suggested that the Ga, Ge, In and other trace-element contents of sphalerite may be used as a geothermometer, and given the variations in Ga content of samples from Round Pond, Twin Ponds and Salmon River #6 this may be a useful discriminator between individual ore bodies.

Further Pb-isotope work is also required, including detailed crustal mapping of the Grenvillian basement. The Pb-isotope signature of galena from base-metal occurrences should be better characterized, using SIMS, Thermal Ionization Mass Spectrometry (TIMS) and/or Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) analyses. As sphalerite is the main ore mineral in these occurrences, it may also be informative to determine the Pb-isotopic signature of sphalerite using MC-ICP-MS analysis,

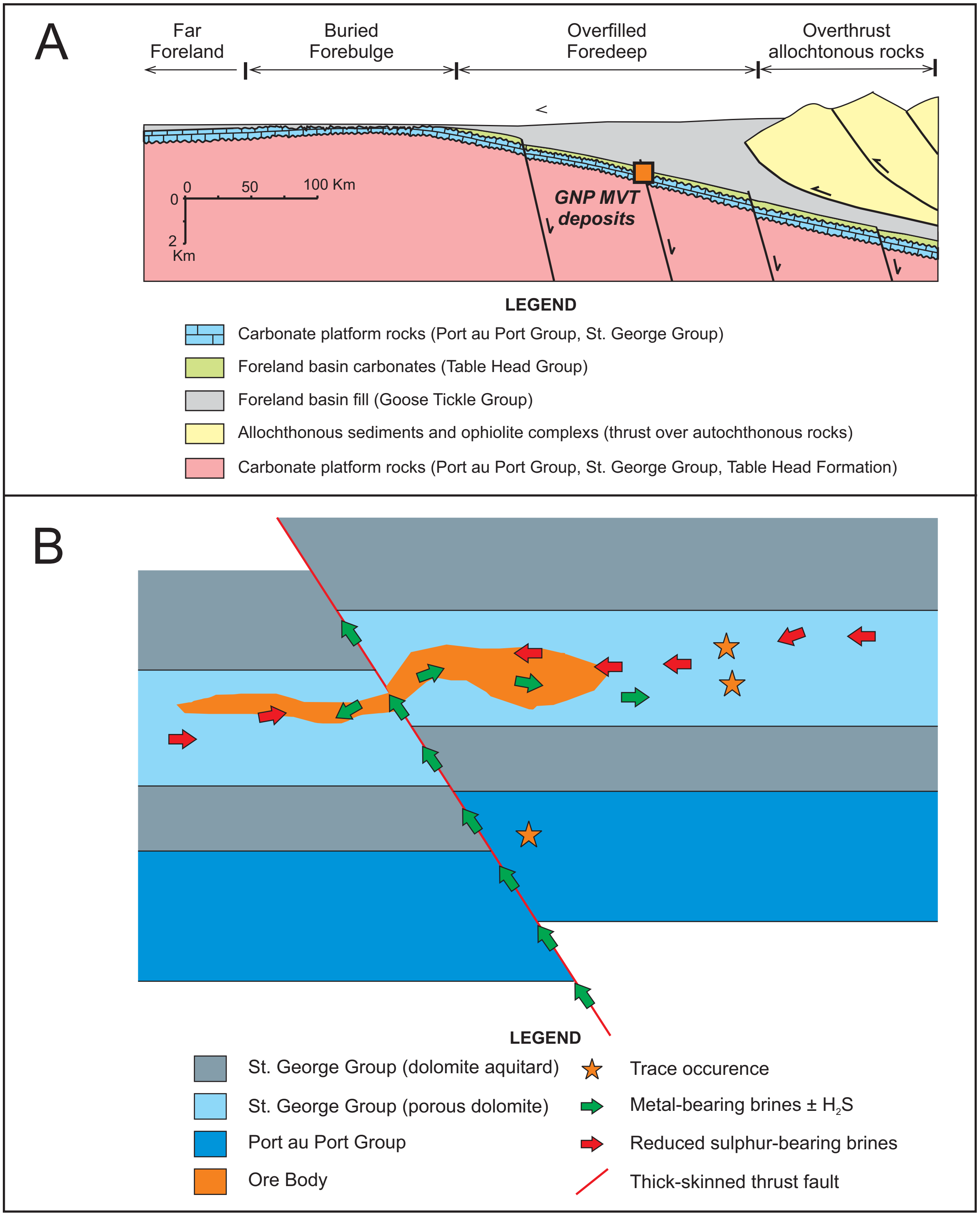

Figure 11. *Genetic model for formation of MVT deposits on the GNP. A) Simplified cross-section of western Newfoundland during the Acadian Orogeny, with numerous thick-skinned reverse faults cutting into the underlying basement rocks. These large crustal structures would act as conduits for metal-bearing fluids to enter the fractured carbonate platform rocks (adapted from Bradley and Leach, 2003); B) Metal-bearing fluids enter St. George Group through network of faults (*e.g., *Ten Mile Fault; Knight, 1986). These fluids would migrate laterally when they encounter porous dolomite strata, and mix with sulphate-rich fluids (possibly Paleozoic seawater expelled from pore spaces during deformation). Sulphides precipitate at the mixing zone* via *TSR.*

as has recently been done in other studies of MVT deposits (*e.g.*, Potra and Moyers, 2017; Field *et al.*, 2018).

In addition, a number of other Zn occurrences in western Newfoundland were visited during fieldwork in 2016. These occurrences are being compared to the occurrences on the GNP with the aim of developing new genetic models and to help develop new exploration strategies.

CONCLUSIONS

Numerous carbonate-hosted Zn (± Pb) occurrences are present in the Hare Bay and Pistolet Bay area of the GNP, Newfoundland. The largest known occurrences are the Round Pond Deposit, Twin Ponds Prospect and Salmon River #6 Prospect. During the summer of 2016, these three occurrences were examined with samples collected for detailed petrographic and geochemical (bulk geochemistry, EPMA analysis, S and Pb isotope) analyses.

The main results of this study are as follows:

- Two forms of sphalerite mineralization have been reported from the Hare Bay area; mineralization hosted in angular fragments of tan, fine-grained dolomite in a white coarse-grained dolomitic cement known as crackle breccia, and hosted in pseudobreccias formed by the selective replacement of fabrics in the host rocks and consisting of mottled grey dolomite with late-stage white dolomitic cement. Both mineralization styles are typical of Mississippi Valley-Type (MVT) deposits, and are similar to mineralization at the Daniel's Harbour Deposit on the GNP.

- Whole-rock geochemical analyses of mineralized grab samples indicate that Zn contents range from 2.0 to 24.5 wt. %, with other major elements reflecting the mineralogy of the host rock (mainly dolomite and calcite). Trace-element analysis shows that the Round Pond and Twin Ponds occurrences are enriched in Ga and Pb, and Salmon River #6 enriched in Cu and Ge.

- The EPMA analysis of sphalerite shows that Fe and Cd are the main trace elements, with significant Cu (51 to 993 ppm) recorded at Salmon River #6. All other trace-element contents are low, with only sporadic values above detection limits. Variations in the Fe and Cd contents are related to mixing of metal-bearing fluids with elevated Cd and sulphur-bearing fluids elevated in Fe.

- The Pb-isotope data are consistent with a crustal source of metals, leached from the Grenvillian basement or the overlying sedimentary rocks. Variations in the Pb-isotope signature of galena from the Round Pond Deposit (*this study*) and the Salmon River #6 Prospect (Swinden *et al.*, 1988) suggest that the mineralizing fluids leached their metals from different crustal sources, consistent with variations in metal contents of samples from these occurrences recorded by whole-rock geochemistry and EPMA analysis.

- Ore precipitation occurred when metal-bearing fluids mixed with crustal sources of sulphur. The source of reduced sulphate is unknown, but may be related to organic material in the carbonates or more likely to sulphate-bearing Paleozoic seawater that was released from the surrounding sedimentary strata during deformation and dehydration. Sulphate reduction occurred *via* TSR at high temperature (>100°C).

- A simplified genetic model for the formation of MVT occurrences on the GNP indicates that mineralization was associated with deformation during the Acadian Orogeny, with metal-bearing brines migrating through Acadian thick-skinned thrust faults and older faults associated with Taconic deformation. These fluids mixed with crustal sulphate in porous dolomite horizons, precipitating sulphide minerals in collapse breccias (crackle breccia) or following the dissolution of the host dolomites (pseudobreccia).

- Future exploration should focus on suitable porous dolomite horizons, with special emphasis on structures that may have been conduits for fluid flow. The presence of well-developed pseudobreccias over a strike length of more than 60 km from Salmon River to North Boat Harbour highlights the exploration potential of this area, and there, good potential exists for the discovery of blind orebodies that do not outcrop at the present erosional surface.

ACKNOWLEDGMENTS

Gerry Hickey provided critical equipment and support for this project without which it would not have been possible. Prospectors Wayde Guinchard and Peter Rogers are thanked for providing drill samples and extra backs for carrying samples. Newfoundland Helicopters brought us to several of our field locations and flew reconnaissance flights over other areas of interest, we would not have been able to keep to our schedule otherwise. Thank you to all the lab staff who helped throughout this project, namely Chris Finch (GSNL Geochemistry Laboratory), Paul Middleton (University of Ottawa) and Wanda Aylward, David Grant, Dylan Goudie, and Glenn Piercey (Memorial University of Newfoundland).

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