



Natural Resources  
Canada

Ressources naturelles  
Canada

**GEOLOGICAL SURVEY OF CANADA  
OPEN FILE 8547**

**Major-, minor-, and trace-element geochemistry  
of sulphide indicator minerals from surficial sediments,  
southwestern Northwest Territories**

**R.D. King, S.J. Piercey, R.C. Paulen, and J.A. Petrus**

**2019**

**Canada** 



## **GEOLOGICAL SURVEY OF CANADA OPEN FILE 8547**

# **Major-, minor-, and trace-element geochemistry of sulphide indicator minerals from surficial sediments, southwestern Northwest Territories**

**R.D. King<sup>1</sup>, S.J. Piercey<sup>1</sup>, R.C. Paulen<sup>2</sup>, and J.A. Petrus<sup>3</sup>**

<sup>1</sup> Department of Earth Sciences, Memorial University of Newfoundland, 9 Arctic Avenue St. John's, Newfoundland and Labrador A1B 3X5

<sup>2</sup> Geological Survey of Canada, 601 Booth Street Ottawa, Ontario K1A 0E8

<sup>3</sup> Mineral Exploration Research Centre, Laurentian University, 935 Ramsay Lake Road, Sudbury, Ontario P3E2C6

**2019**

© Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources, 2019

Information contained in this publication or product may be reproduced, in part or in whole, and by any means, for personal or public non-commercial purposes, without charge or further permission, unless otherwise specified.

You are asked to:

- exercise due diligence in ensuring the accuracy of the materials reproduced;
- indicate the complete title of the materials reproduced, and the name of the author organization; and
- indicate that the reproduction is a copy of an official work that is published by Natural Resources Canada (NRCan) and that the reproduction has not been produced in affiliation with, or with the endorsement of, NRCan.

Commercial reproduction and distribution is prohibited except with written permission from NRCan. For more information, contact NRCan at [nrcan.copyrightdroitdauteur.nrcan@canada.ca](mailto:nrcan.copyrightdroitdauteur.nrcan@canada.ca).

Permanent link: <https://doi.org/10.4095/314688>

This publication is available for free download through GEOSCAN (<https://geoscan.nrcan.gc.ca/>).

### **Recommended citation**

King, R.D., Piercey, S.J., Paulen, R.C., and Petrus, J.A., 2019. Major-, minor-, and trace-element geochemistry of sulphide indicator minerals from surficial sediments, southwestern Northwest Territories; Geological Survey of Canada, Open File 8547, 1 .zip file. <https://doi.org/10.4095/314688>

## TABLE OF CONTENTS

<b>Abstract</b> .....	<b>1</b>
<b>Introduction</b> .....	<b>1</b>
<b>Methods</b> .....	<b>2</b>
<b>Results</b> .....	<b>3</b>
<b>Discussion</b> .....	<b>6</b>
<b>Summary</b> .....	<b>8</b>
<b>Acknowledgements</b> .....	<b>8</b>
<b>References</b> .....	<b>9</b>

### Appendices

**Appendix A.** Major and trace element geochemical data for sphalerite grains from samples collected in the study area.

**Appendix B.** Major and trace element geochemical data for galena grains from samples collected in the study area.

**Appendix C.** Major and trace element geochemical data for chalcopyrite grains from samples collected in the study area

**Appendix D.** Major and trace element geochemical data for arsenopyrite grains from samples collected in the study area

### Figures

Figure 1. Location map of study area .....	2
Figure 2. Simplified bedrock geology map showing sample locations .....	4
Figure 3. Fe versus Zn bivariate plot of sphalerite grains from the study area and from Pine Point, various seafloor hydrothermal systems along the Mid Atlantic Ridge, Central Indian Ridge, and Okinawa .....	5
Figure 4. Ge versus In bivariate plot of sphalerite grains from the study area and from skarn, volcanogenic massive sulphide, and stratabound deposits .....	6
Figure 5. Ag versus Sb+Bi bivariate plot of galena grains from the study area and deposits of varying temperature .....	8

# Major-, minor-, and trace-element geochemistry of sulphide indicator minerals from surficial sediments, southwestern Northwest Territories

Robert D. King<sup>1</sup>, Stephen J. Piercey<sup>1</sup>, Roger C. Paulen<sup>2</sup>, and Joe A. Petrus<sup>3</sup>

<sup>1</sup> Department of Earth Sciences, Memorial University, 9 Arctic Avenue St. John's, NL, A1B 3X5

<sup>2</sup> Geological Survey of Canada, 601 Booth Street Ottawa, ON, K1A 0E8

<sup>3</sup> Mineral Exploration Research Centre, Laurentian University, 935 Ramsay Lake Road, Sudbury, ON, P3E2C6

## Abstract

Till sample surveys were conducted near the headwaters of the Mackenzie River in 2007, 2008, and 2012, as part of the Northwest Territories Geological Survey's Protected Area Strategy surveys. Numerous sphalerite, galena, chalcopyrite, and arsenopyrite grains were recovered from many of the till samples. No proximal, up-ice mineralized bedrock source for these sulphide grains has been found to date, with the nearest known outcropping bedrock source of sphalerite and galena being the Qito Pb-Zn showing (~274 km to the northeast) and the Pine Point Mississippi Valley-type (MVT) Pb-Zn deposit (~400 km to the east). The sulphide indicator mineral grains were analysed via electron probe micro analysis and laser ablation-inductively coupled plasma-mass spectrometry to determine their major, minor and trace elemental composition to elucidate their potential bedrock source and to characterize the potential host mineralization type. Sphalerite grains are Fe-poor, having up to 5.07 wt% (6.38 mol% FeS) with Cd abundances up to 2.21 wt% (0.97 mol% CdS); they also have variable Cu, Ga, Ge, In, Ag, Sn, As, Te, Sb, and Bi. Most trace elements in galena are below the limit of detection with the exception of Ag, Cd, In, Sn, Sb, Te, and Bi. Similarly, most trace elements in chalcopyrite are in low abundance, with the exception of Zn, Ge, As, Se, Ag, In, Sn, and Bi. Arsenopyrite grains contain Co, Ni, Cu, Ge, Se, Ag, In, Sb, Te, Au, and Bi; all other elements analysed are below the detection limit. The trace element compositions of sphalerite and galena are indicative of deposition in a low temperature (and low  $a_{S_2}$ ) environment, such as carbonate-hosted MVT Pb-Zn mineralization. Chalcopyrite and arsenopyrite mineral chemical data do not provide signatures that are diagnostic of a specific deposit type.

## Introduction

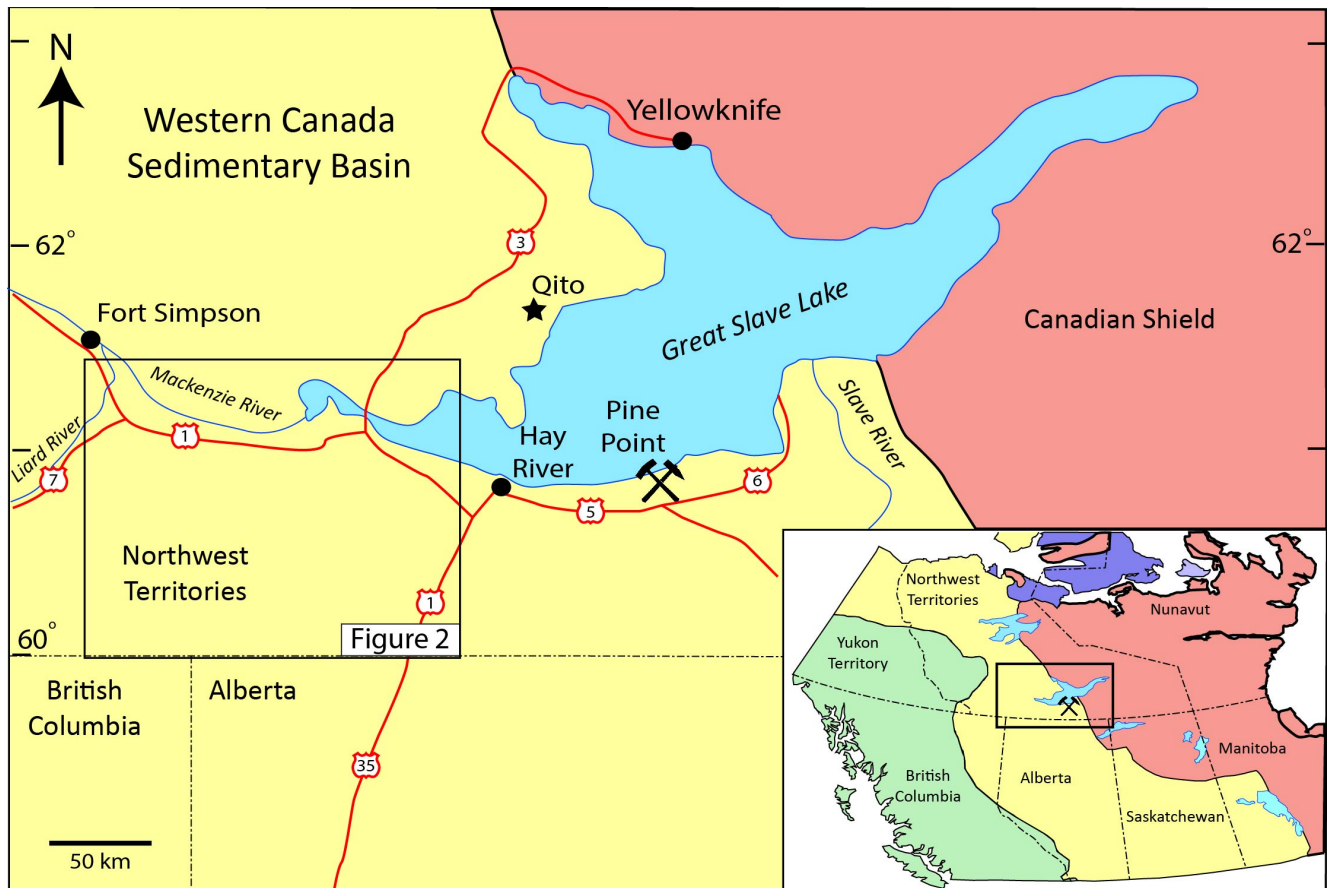
Regional till sample surveys were conducted in the Sambaa K'e (Trout Lake region), Ka'a'gee Tu (Kakisa Lake region) and Lue Túé Súlái (Jean Marie River region), southwestern Northwest Territories as part of the Protected Area Strategy (PAS) assessments conducted by the Northwest Territories Geological Survey from 2007 to 2012 (Fig 1; Watson, 2011a, b; Watson, 2013). The till sample surveys identified high indicator mineral counts of several sulphide species, including sphalerite (up to 334 grains, normalized to 25 kg sample weight), galena (up to 28 grains, normalized to 25 kg sample weight), chalcopyrite (up to 31 grains, normalized to 25 kg sample weight) and arsenopyrite (up to 3 grains, normalized to 25 kg sample weight) of which there is no known up-ice bedrock source proximal to the survey areas (Fig 2; Watson, 2011a, b; Watson 2013; King et al., 2018). The region is host to several

carbonate-hosted Pb-Zn occurrences, both at depth in NTS map sheet 85B and outcropping in the northern part of NTS map sheet 85F (Qito), as well as polymetallic vein-hosted Cu in map sheet 95G (Fig. 2; Dudek, 1993; Paradis et al., 2006). Previous Pb- and S-isotope work on PAS grains determined that sulphides were not likely sourced from Pine Point or Qito, thus warranting further geochemical work to determine potential deposit origins (King et al., 2018). Herein, we report major, minor, and trace element geochemistry compositions of sulphide indicator minerals determined using electron-probe microanalysis (EPMA) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). This research focuses on determining the provenance of these sulphide indicator minerals.

## Methods

Picked sulphide indicator minerals from the 0.25-2.0 mm size fraction from 39 samples collected throughout the region (Fig 2) were provided by the Northwest Territories Geological Survey and mounted in 25 mm epoxy pucks and carbon-coated prior to analysis using a JEOL JSM 7100F field emission scanning electron microscope (SEM) equipped

with a Thermo energy dispersive X-ray spectrometer at the Department of Earth Sciences, Memorial University of Newfoundland. Each grain was imaged using a 15.0 kV beam in backscatter and secondary electron. In addition to SEM imaging, each grain was analysed at two points (one each, core and rim) to qualitatively determine the chemistry of the grains and validate identification during the mineral separation process.



**Figure 1.** Regional geology map of the southern Northwest Territories showing the study area. Inset map shows the Canadian Shield (red), Western Canada Sedimentary Basin (yellow) and the Canadian Cordillera (green) (modified from Oviatt et al., 2015).

Epoxy-mounted grains of sphalerite (n=48), galena (n=6), chalcopyrite (n=18) and arsenopyrite (n=7) were later analysed using a JEOL JXA-8230 microprobe equipped with a W source and 5 wavelength dispersive spectrometers at the Department of Earth Sciences, Memorial University of Newfoundland. A series of mineral and metallic standards were used for calibration. Each grain was analysed at two points with a 20nA beam and a 20kV accelerating voltage, which measured the weight percent abundance of Ni, Co, Ga, Zn, Cu, Fe, Sb, Cd, S, Se, As, Ag, Au, and Pb present in the grains. Electron microprobe data were later used to internally calibrate LA-ICP-MS results.

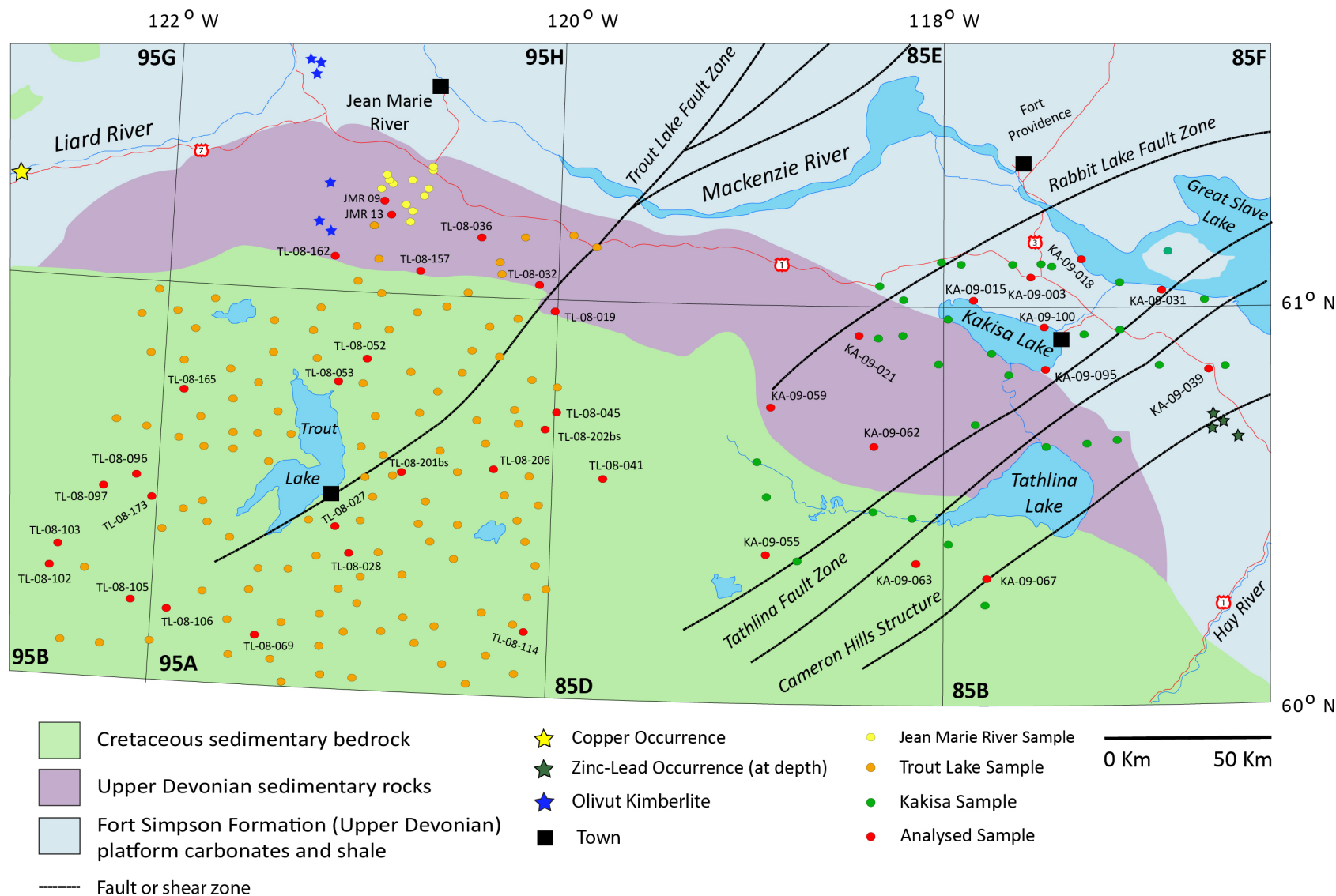
LA-ICP-MS analyses were completed on all sulphide phases to determine the trace element composition for 29 elements (isotopes analysed:  $^{33}\text{S}$ ,  $^{55}\text{Mn}$ ,  $^{57}\text{Fe}$ ,  $^{59}\text{Co}$ ,  $^{60}\text{Ni}$ ,  $^{65}\text{Cu}$ ,  $^{66}\text{Zn}$ ,  $^{69}\text{Ga}$ ,  $^{71}\text{Ga}$ ,  $^{72}\text{Ge}$ ,  $^{73}\text{Ge}$ ,  $^{75}\text{As}$ ,  $^{77}\text{Se}$ ,  $^{82}\text{Se}$ ,  $^{107}\text{Ag}$ ,  $^{111}\text{Cd}$ ,  $^{113}\text{In}$ ,  $^{115}\text{In}$ ,  $^{118}\text{Sn}$ ,  $^{121}\text{Sb}$ ,  $^{125}\text{Te}$ ,  $^{197}\text{Au}$ ,  $^{202}\text{Hg}$ ,  $^{204}\text{Pb}$ ,  $^{205}\text{Tl}$ ,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$ ,  $^{208}\text{Pb}$ , and  $^{209}\text{Bi}$ ) using a Thermo X-Series II ICP-MS with a Resonetics RESolution M-50 laser at the Harquail School of Earth Sciences, Laurentian University. Analyses were performed using a 193 nm wavelength ArF excimer laser with a 20 ns pulse duration. The mass spectrometer was operated with a forward power of 1440 W. Spots previously analysed by EPMA were analysed using a beam diameter of 55  $\mu\text{m}$  with a repetition rate of 8 Hz and an energy density of 3 J/cm<sup>2</sup>. Ablation took place in a Laurin Technic two-volume ablation cell (Müller et al., 2009) in a He atmosphere (650 ml/min). After exiting the ablation chamber, the ablated material and He were mixed with Ar (800 ml/min) and N<sub>2</sub> (6 ml/min) which travelled to the torch via ~3 m of nylon 6 tubing. Data were processed using iolite v.3.4 (Paton et al., 2011) using the trace element data reduction scheme with Zn/GSE, Pb/GSE, Fe/GSE, and Fe/GSE as the internal/external

references for quantification for the sphalerite, galena, chalcopyrite, and arsenopyrite, respectively (Jochum et al., 2006).

## Results

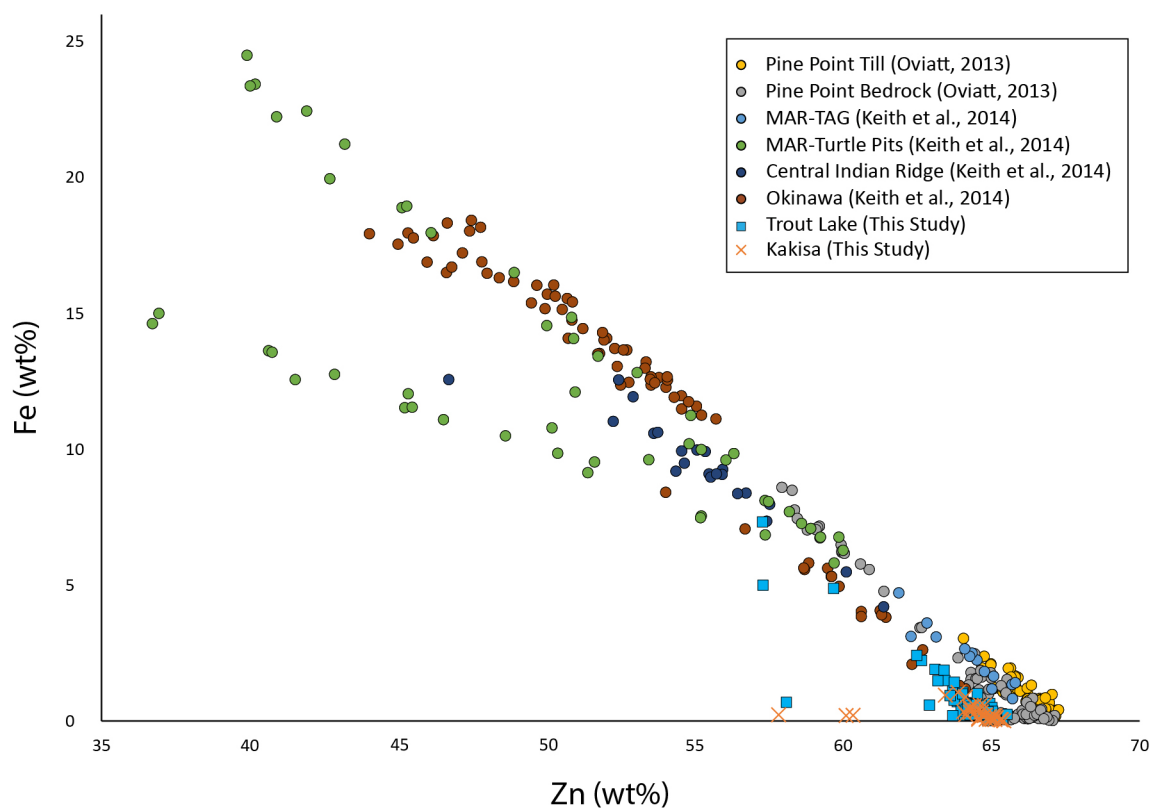
### *Sphalerite*

Sphalerite grains recovered from the PAS samples are generally stoichiometric, having Zn and S contents ranging from 57.29 to 65.53 wt% and 25.95 to 34.98 wt%, respectively. The Fe and Cd contents are from 0.01 to 5.07 wt% (up to 6.38 mol% FeS) and below the detection limit to 2.21 wt% (up to 0.97 mol% CdS), respectively (Appendix A). The weight percent Zn and Fe for the sphalerite grains is plotted in Figure 3 along with values for sphalerite analysed from till and bedrock sources near Pine Point (Oviatt, 2013); these values are compared with submarine hydrothermal vents of varying temperatures (Keith et al., 2014). Copper, Ga, Ge and In contents of up to 931.00, 840.00, 731.00, and 154.80 ppm, respectively, are present in some samples. One sphalerite contains up to 174.40 ppm of Se from a till sample collected at the southwest margin of the survey area (sample TL-08-103). Other trace elements analysed, including Ag, Sn, As, Te, Sb, and Bi have up to 4.70, 54.00, 2.71, 0.69, 57.50, and 0.61 ppm, respectively. Germanium and In data are plotted in Figure 4 and are compared to values from other deposits studied by Cook et al. (2009) and Ye et al. (2011), including stratabound, massive sulphide (both volcano-genic and sedimentary exhalative), proximal skarn, and distal skarn deposits. Data from Trout Lake grains plot with high Ge and low In, similar to stratabound deposits studied by Cook et al. (2009) and Ye et al. (2011), while Kakisa samples plot as having lower Ge and high In, plotting in similar fields to other higher temperature hydrothermal systems (Cook et al., 2009; Ye et al., 2011).



**Figure 2.** Simplified bedrock geology (after Douglas, 1974; Okulitch, 2006) showing the location of samples provided by the Northwest Territories Geological Survey, denoted by yellow, orange, and green circles (Watson, 2011 a,b, 2013). Red circles indicate samples analysed in the present study. The location of kimberlites is marked by blue stars (Pitman, 2014). Copper and zinc-lead occurrences are indicated by yellow and dark green stars, respectively (Dudek, 1993; Paradis et al., 2006).





**Figure 3.** Scatterplot of wt% Fe versus Zn in sphalerite from this study. Data is compared to values from various seafloor hydrothermal systems including the Mid Atlantic Ridge (MAR), the Central Indian Ridge, and the Okinawa Trough (Keith et al., 2014). The lower trend observed in samples from MAR Turtle Pit is due to chalcopyrite disease in sphalerite samples (Keith et al., 2014).

### Galena

Lead contents in galena range from 85.79 to 86.60 wt% and S from 13.31 to 13.64 wt% (Appendix B). Most trace elements in galena grains are less than the lower limit of detection (Appendix B), with the exception of Ag, Cd, In, Sn, Sb, Te, and Bi which have contents of up to 1.20, 14.46, 0.011, 0.04, 12.99, 0.29, and 12.60 ppm, respectively.

### Chalcopyrite

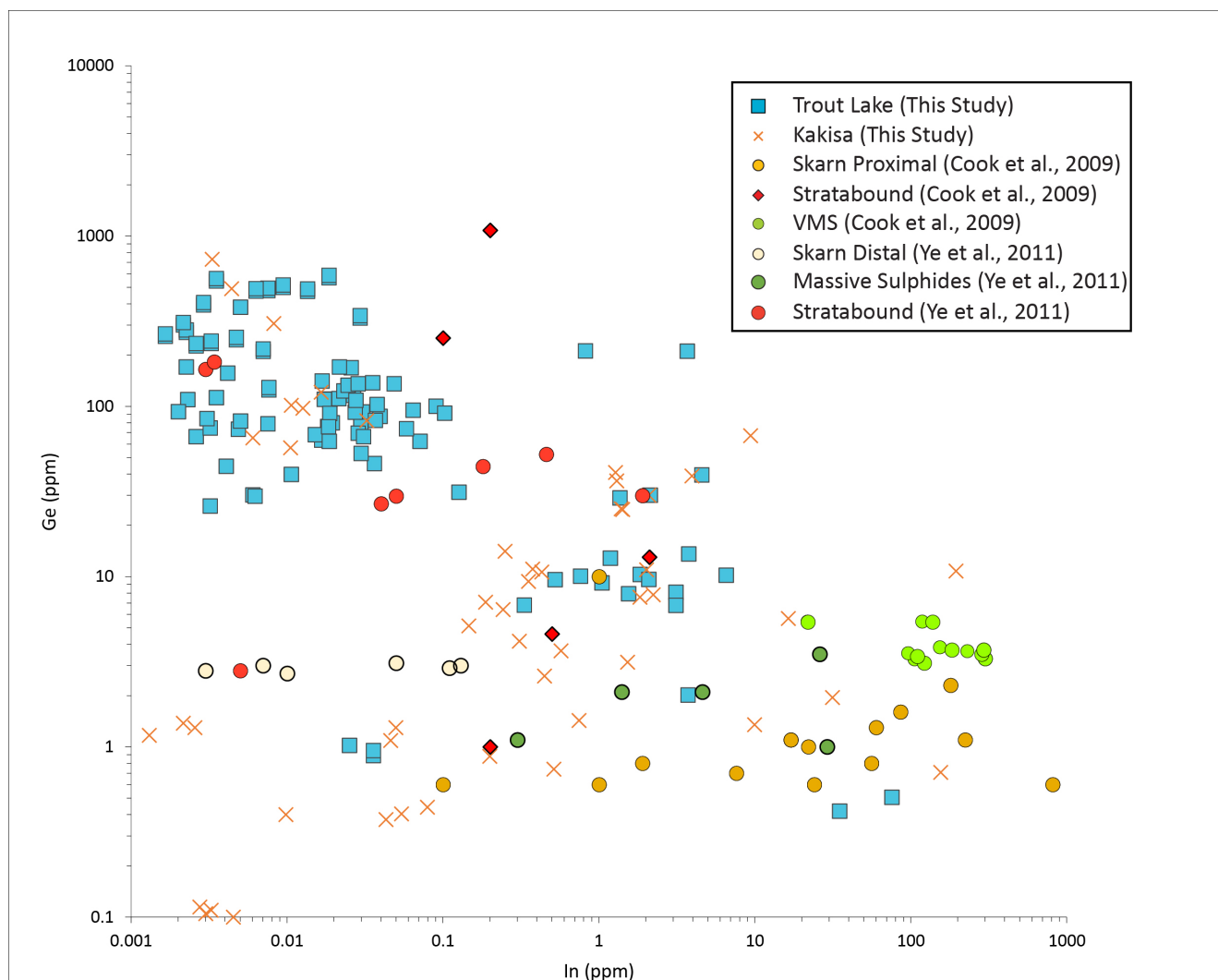
Chalcopyrite grains have 33.02 to 33.88 wt% Cu, 29.83 to 30.56 wt% Fe and 34.66 to 35.09 wt% S with trace Mn, Ni, Ga, Cd, Te, and Au

(Appendix C). Samples contain up to 3500 ppm of Zn, 101.50 ppm of Ge, 585.00 ppm of As, 225.00 ppm of Se, 11.34 ppm of Ag, 8.92 ppm of In, 23.76 ppm of Sn, and 31.60 ppm of Bi.

### Arsenopyrite

Grains of arsenopyrite have 30.29 to 34.07 wt% Fe, 17.12 to 21.96 wt% S and 42.04 to 48.64 wt% As (Appendix D). The arsenopyrite grains also contain up to 1.6 wt% Co, 7460 ppm of Ni, 3.34 ppm of Cu, 0.54 ppm of Ge, 42.3 ppm of Se, 21.8 ppm of Ag, 1.64 ppm of In, 160.90 ppm of Sb, 629 ppm of Te, 0.49 ppm of Au, and 26.80 ppm of Bi.





**Figure 4.** Scatterplot of  $\text{Ge}^{72}$  versus  $\text{In}^{115}$  from sphalerite grains from this study. Data is plotted against values from various deposit types studied by Cook et al. (2009) and Ye et al. (2011). Higher Ge content indicates lower temperature ore systems where as high In is indicative of higher temperature systems (Cook et al., 2009; Ye et al., 2011). Note logarithmic scale.

## Discussion

Many authors have shown that the Fe content of sphalerite is largely controlled by temperature and oxygen and sulphur fugacity of the fluids from which they precipitated (Scott and Barnes, 1971; Scott and Kissin, 1973; Sack and Ebel, 2000; Cook et al., 2009; Keith et al., 2014). Iron (II) substitutes for  $\text{Zn}^{2+}$  and can be present in contents of up to 25 wt% Fe in sphalerites crystallized at higher temperatures ( $T \geq 400^\circ\text{C}$ ) but are much lower in sphalerite derived from low temperature hydrothermal fluids (Fig 3;

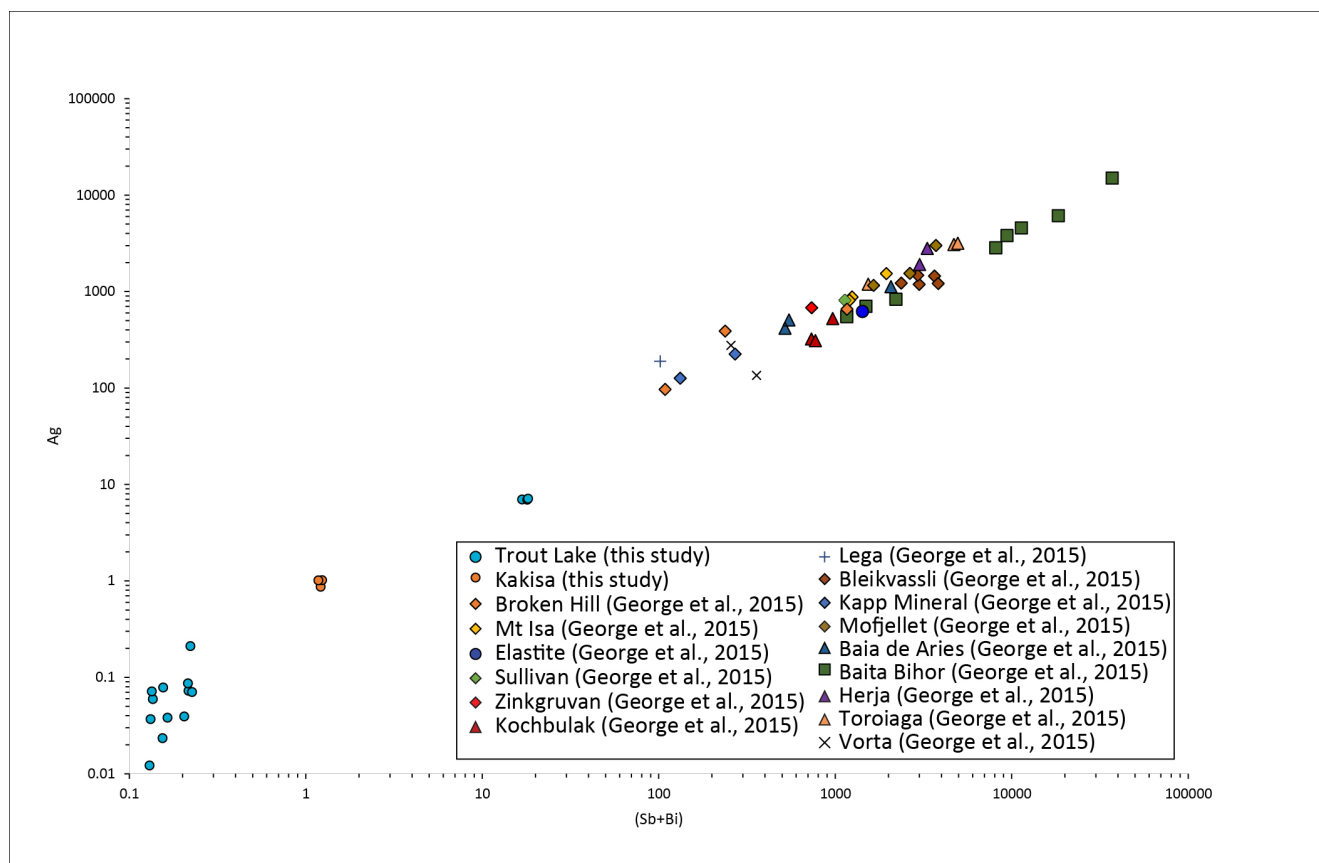
Keith et al., 2014). Sphalerite grains from this study (Fig. 3) have similar ranges to samples from the Pine Point mining district, with relatively low Fe contents (Oviatt, 2013; Oviatt et al., 2015). Fluid temperatures for the Pine Point MVT deposits have been estimated at  $50\text{--}100^\circ\text{C}$  (Rhodes et al., 1984). Further, when compared to global estimates for high temperature sphalerites (e.g. volcanogenic massive sulphide (VMS) deposit sphalerite; Keith et al., 2014), the Fe values are much lower and suggests that the sphalerites in this study may have formed in a low temperature fluid.

The trace element contents of sphalerite are also useful for potentially determining deposit type of origin. For example, Cook et al. (2009) illustrated that Ge and In concentrate in sphalerite at different crystallization temperatures. Indium tends to be enriched in sphalerite formed at higher temperatures ( $T > 250^{\circ}\text{C}$ ; e.g., VMS, skarns, magmatic-hydrothermal deposits; Fig 4; Cook et al., 2009; Ye et al., 2011). In contrast, Ge is enriched at lower mineralization temperatures ( $T < 250^{\circ}\text{C}$  e.g., MVT; Cook et al., 2009; Ye et al., 2011). A significant number of sphalerite grains from this study, particularly from the Trout Lake region (26/31 grains), are generally enriched in Ge and depleted in In similar to those found in stratabound deposits (Fig. 4; Cook et al., 2009; Ye et al., 2011). Nevertheless, several samples from the Kakisa region returned Ge and In concentrations that plot closer to values from proximal skarn and massive sulphide deposits, indicating potentially higher depositional temperatures for some sphalerite grains (Fig 4; Cook et al., 2009; Ye et al., 2011). The vast majority, however, indicate lower temperature origins, likely from carbonate-hosted Pb-Zn mineralization as proposed previously using S and Pb isotopic arguments (e.g., King et al., 2018). Those with higher In values may indicate grains precipitated closer to fluid conduits in the region or indicate potential for higher temperature systems in the region (e.g. manto/Kipushi-type; Runnels, 1969; Dudek, 1993; Hannigan, 2006).

Certain trace elements partition into galena during crystallization with partitioning influenced by oxidation state, ionic radius, and element availability (George et al., 2015; 2016). Elements such as Ag, Sb, and Bi, are affected mostly by temperature, where the coupled

substitution of  $\text{Ag}^+ + (\text{Bi,Sb})^{3+} \leftrightarrow \text{Pb}^{2+}$  is most efficient at temperatures between 350 and 400  $^{\circ}\text{C}$ ; at these temperatures galena can incorporate up to several weight percent Ag (Foord et al., 1988; Foord and Shawe, 1989; George et al., 2015). Galena grains in this study have low Ag, Bi and Sb contents compared to higher temperature deposits (Fig 5), suggesting that galena grains from this study precipitated at low temperatures (George et al., 2015). This is corroborated by sulphur isotope data from the same samples that support derivation from MVT-style mineralization (Rhodes et al., 1984; King et al., 2018). Although the Pine Point Pb-Zn mine (or Qito showing) is the geographically closest known MVT district, the galena (and sphalerite) grains have features that are inconsistent with the Pine Point district and are not thought to have originated therefrom (e.g., King et al., 2018), and indicate derivation from undiscovered MVT-style mineralization (King et al., 2018).

The results of this study were unable to resolve deposit origin for chalcopyrite and arsenopyrite. In chalcopyrite, the necessary elements for plotting and differentiating hydrothermal or magmatic origin (Cd, Ni, and Se) were below the lower limit of detection of LA-ICP-MS (Duran et al., 2018; George et al., 2018). Similarly, arsenopyrite compositions were undiagnostic, and without known mineral associations, assessment of potential source deposits is impossible (Sharpe et al., 1985). However, based on the abundances of each mineral in samples and other isotopic evidence data chalcopyrite grains are likely of local origin, whereas arsenopyrite grains were dispersed from farther up-ice from the Canadian Shield (King et al., 2018).



**Figure 5.** Scatterplot of Ag versus Sb+Bi abundances in galena from this study compared to data from various deposits (George et al., 2015). Ag and Sb+Bi correlate well, with concentrations increasing with temperature, generally (George et al., 2015). High values from Baita Bihor are the result of enriched Bi content for the region (George et al., 2015). Note logarithmic scale.

## Summary

EPMA and LA-ICP-MS analyses of base metal indicator minerals recovered from surficial samples in the southern Northwest Territories suggest that sphalerite and galena grains formed in lower temperature hydrothermal fluids, possibly in an MVT environment (Fig. 3, 4 and 5). Trace element data for chalcopyrite and arsenopyrite grains are inconclusive as many of the trace element abundances are below detection, inhibiting the ability to assess potential deposit types of origin; however, given the regional metallogeny of the area and other lines of evidence (e.g., King et al., 2018), it is possible that chalcopyrite grains were sourced from proximal mineralization and arsenopyrite grains were dispersed from orogenic Au systems in the Canadian Shield.

## Acknowledgments

The sulphide indicator minerals were provided by the Northwest Territories Geological Survey as part of a collaborative project with the Geological Survey of Canada's Geomapping for Energy and Minerals GEM-2 program, Southern Mackenzie Surficial activity. Additional funding to support this work was provided by Stephen J. Piercey (NSERC Discovery Grant). The authors would like to acknowledge Glenn Piercey (Memorial University) for assistance in mounting samples. Additionally, Dr. Wanda Aylward (Memorial University) is thanked for assistance with preliminary SEM imaging as well as aiding with microprobe analyses. We thank Jan Peter and Michael Gadd for their scientific reviews of this report.

## References

- Bednarski, J.M., 2008. Quaternary geology of Fort Liard map area, Northwest Territories; Geological Survey of Canada, Bulletin 596, 59 p. doi:10.4095/225608
- Cook, N.J., Ciobanu, C.L., Meria, D., Silcock., and Wade, B., 2013. Arsenopyrite-pyrite Association in an Orogenic Gold Ore: Tracing Mineralization History from Textures and Trace Elements; *Economic Geology*, v. 108, p. 1273-1283. 0361-0128/13/4139/1273-11
- Cook, N.J., Ciobanu, C.L., Pring, A., Skinner, W., Massaaki, S., Danyushevsky, L., Saini-Eidukat, B., and Melcher, F., 2009. Trace and minor elements in sphalerite: A LA-ICP-MS study. *Geochemica et Cosmochimica Acta*, 73: p. 4761-4791. doi:10.1016/j.gca.2009.05.045
- Douglas, R.J.W., 1974. Geology, Trout River, District of Mackenzie; Geological Survey of Canada, Map 1371A, scale 1: 500,000. doi.org/10.4095/109150
- Dudek, D., 1993. Report of Geological work and drilling carried out on the Moisey Property, Mackenzie District, Northwest Territories; Noranda Exploration Company Ltd., Northwest Territories Geoscience Office, Assessment Report 083110.
- Duran, C.J., Dudé-Loubert, H., Pagé, P., Barnes, S.J., Roy, M., Savard, D., Cave, Arguin, J.P., Mansur, E.D., 2019. Applications of trace element chemistry of pyrite and chalcopyrite in glacial sediments to mineral exploration targeting: Example from the Churchill Province, northern Quebec, Canada; *Journal of Geochemical Exploration*, 196, p. 105-130. doi.org/10.1016/j.gexplo.2018.10.006
- Foord, E.E., and Shawe, D.R., 1989. The Pb-Bi-Ag-Cu-(Hg) chemistry of galena and some associated sulfosalts: a review and some new data from Colorado, California and Pennsylvania; *Canadian Mineralogist*, 27, 363–382.
- Foord, E.E., Shawe, D.R., and Conklin, N.M., 1988. Coexisting galena, PbS, and sulfosalts: evidence for multiple episodes of mineralization in the Round Mountain and Manhattan gold districts, Nevada; *Canadian Mineralogist*, 26, 355–376.
- George, L.L., Cook, N.J., Ciobanu, C.L., 2016. Partitioning of trace elements in co-crystallized sphalerite-galena-chalcopyrite hydrothermal ores; *Ore Geology Reviews*, 77, p. 97-116. doi.org/10.1016/j.oregeorev.2016.02.009
- George, L.L., Cook, N.J., Ciobanu, C.L., and Wade, B.P., 2015. Trace and minor elements in galena: A reconnaissance LA-ICP-MS study; *American Mineralogist*, 100, p. 548-569. doi.org/10.2138/am-2015-4862
- George, L.L., Cook, N.J., Crowe, B.B.P., Ciobanu, C.L., 2018. Trace elements in hydrothermal chalcopyrite; *Mineralogical Magazine*, 82, p. 59-88. doi.org/10.1180/minmag.2017.081.021
- Hannigan, P.K., 2006. Synthesis of Mississippi Valley-type lead-zinc deposit potential in northern Alberta and southern Northwest Territories, *In*; *Potential for Carbonate-hosted Lead-zinc Mississippi Valley-type Mineralization in Northern Alberta and Southern Northwest Territories: Geoscience Contributions, Targeted Geoscience Initiative*, (ed.) P.K. Hannigan; Geological Survey of Canada, Bulletin 591, p. 305–347.

- Jochum, K.P., Stoll, B., Herwig, K., Willbold, M., Hofmann, A.W., Amini, M., Aarburg, S., Abouchami, W., Hellebrand, E., Mocek, B., Raczek, I., Stracke, A., Alard, O., Bouman, C., Becker, S., Dücking, M., Brätz, H., Klemm, R., Bruin, D.d., Canil, D., Cornell, D., Hoog, C.-J.d., Dalpe, C., Danyushevsky, L., Eisenhauer, A., Gao, Y., Snow, J.E., Groschopf, N., Günther, D., Latkoczy, C., Guillong, M., Hauri, E.H., Höfer, H.E., Lahaye, Y., Horz, K., Jacob, D.E., Kasemann, S.A., Kent, A.J.R., Ludwig, T., Zack, T., Mason, P.R.D., Meixner, A., Rosner, M., Misawa, K., Nash, B.P., Pfänder, J., Premo, W.R., Sun, W.D., Tiepolo, M., Vannucci, R., Vennemann, T., Wayne, D., Woodhead, J.D., 2006. MPI-DING reference glasses for in situ microanalysis: new reference values for element concentrations and isotope ratios; *Geochemistry Geophysics Geosystems*. 7(2). doi:10.1029/2005GC001060
- Keith, M., Haase, K.M., Schwarz-Schampera, U., Klemm, R., Petersen, S., and Bach, W., 2014. Effects of temperature, sulfur, and oxygen fugacity on the composition of sphalerite from submarine hydrothermal vents; *Geology*. 41, 8, p. 699-702. doi:10.1130/G35655.1
- King, R.D., Piercey, S.J., and Paulen, R., 2018. In situ, microanalytical sulphur and lead isotopic compositions of sulphide indicator minerals from surficial sediments in southwestern Northwest Territories; Geological Survey of Canada, Open File 8449, 1 zip file. <https://doi.org/10.4095/>
- Müller, W., Shelley, M., Miller, P., and Broude, S. 2009. Initial performance metrics of a new custom-designed ArF excimer LA-ICPMS system coupled to a two-volume laser-ablation cell. *Journal of Analytical Atomic Spectrometry*, 24(2), 209-214.
- Okulitch, A.V. (comp.), 2006. Phanerozoic bedrock geology, Slave River, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Open File 5281, scale 1:1,000,000. doi:10.4095/222163
- Oviatt, N.M., 2013. Characterization of indicator minerals and till geochemical dispersal patterns associated with the Pine Point Pb-Zn Mississippi Valley-type Deposits, Northwest Territories, Canada; MSc thesis, University of Alberta, 208p.
- Oviatt, N.M., Gleeson, S.A., Paulen, R.C., McClenaghan, M.B., and Paradis, S., 2015. Characterization and glacial dispersal of indicator minerals associated with the Pine Point Mississippi Valley-type (MVT) district, Northwest Territories, Canada; *Canadian Journal of Earth Sciences*, v. 52, p. 776–794. doi:10.1139/cjes-2014-0108
- Paradis, S., Turner, W.A., Coniglio, M., Wilson, N., and Nelson, J.L., 2006. Stable and radiogenic isotopic signatures of mineralized Devonian carbonates of the Northern Rocky Mountains and the Western Canada Sedimentary Basin, In *Potential for Carbonate-Hosted Lead-zinc Mississippi Valley-type Mineralization in Northern Alberta and Southern Northwest Territories: Geoscience Contributions, Targeted Geoscience Initiative*, (ed.) P.K. Hannigan; Geological Survey of Canada, Bulletin 591, p. 75–104. doi:10.4095/222922
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., and Hergt, J. 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, 26, p. 2508-2518.

- Pettke, T., Oberli, F., Audétat, A., Guillong, M., Simon, A.C., Hanley, J.J., and Klemm, L.M. 2012. Recent developments in element concentration and isotope ratio analysis of individual fluid inclusions by laser ablation single and multiple collector ICP-MS; *Ore Geology Reviews*, v. 44, p. 10-38.
- Pitman, P., 2014. Technical report on the HOAM Project, Northwest Territories Canada, NTS map sheets 85L, 85M, 95A, 95G, 95H, 95I, 95O, 95P, 96A and 96B; Olivut Resources, National Instrument 43-101 Technical Report ([www.sedar.com](http://www.sedar.com)).
- Plouffe, A., Paulen, R.C., Smith, I.R., and Kjarsgaard, I.M., 2007. Chemistry of kimberlite indicator minerals and sphalerite derived from glacial sediments of northwest Alberta; Alberta Energy and Utilities Board, Alberta Geological Survey, Special Report 87, Geological Survey of Canada, Open File 5545.
- Rhodes, D., Lantos, E.A., Lantos, J.A., Webb, R.J., and Owens, D.C., 1984. Pine Point orebodies and their relationship to the stratigraphy, structure, dolomitization, and karstification of the middle Devonian Barrier complex; *Economic Geology*, v. 79, p. 991–1055.
- Runnels, D.D. 1969. The Mineralogy and Sulfur Isotopes of the Ruby Creek Copper Prospect, Bornite, Alaska. *Economic Geology*, v. 64, p. 75-90.
- Sack, R.O., and Ebel, D.S., 2006. Thermochemistry of Sulfide Mineral Solutions; *Reviews in Mineralogy and Geochemistry*, v. 61, p. 265-364. DOI: 10.2138/rmg.2006.61.6
- Scott, S.D., and Barnes, H.L., 1971. Sphalerite Geothermometry and Geobarometry; *Economic Geology*, v. 66, p. 653-669.
- Scott, S.D., and Kissin, S.A., 1973. Sphalerite Composition in the Zn-Fe-S System below 300 °C; *Economic Geology*, v. 68, p. 475-479.
- Sharp, Z.D., Essene, E.J., and Kelly, W.C., 1985. A re-examination of the arsenopyrite geothermometer: Pressure considerations and applications to natural assemblages\*; *Canadian Mineralogist*, v. 23, p. 517-534.
- Watson, D.M., 2011a. Sambia K'e Candidate Protected Area Phase II Non-renewable Resource Assessment – Minerals, Northwest Territories, Parts of NTS 085D, 095A, B, H; Northwest Territories Geoscience Office, NWT Open File 2010-08.
- Watson, D.M., 2011b. Ka'a'gee Tu Area of Interest, Phase II Non-renewable Resource Assessment – Minerals, Northwest Territories, Parts of NTS 85C, 85D, 85E and 85F; Northwest Territories Geoscience Office, NWT Open File 2011-001.
- Watson, D.M., 2013. Non-Renewable Resource Assessment (Minerals): Łue Túé Súlái Candidate Protected Area, NTS 095H6 & 095H7; Northwest Territories Geoscience Office, NWT Open File 2013-03.
- Ye, L., Cook, N.J., Ciobanu, C.L., Yuping, L., Qian, Z., Tiegeng, L., Wei, Gao., Yulong, Y., and Danyushevskiy, L., 2011. Trace and minor elements in sphalerite from base metal deposits in South China: A LA-ICP-MS study; *Ore Geology Reviews*, 39, p. 188-217.  
doi:10.1016/j.oregeorev.2011.03.001