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ABSTRACT

This report presents analytical data from sphalerite, galena, chalcopyrite, and arsenopyrite grains recovered during recent surficial sampling programs in the region southwest of the headwaters of the Mackenzie River, Northwest Territories. Many samples were found to contain high numbers of sulphide mineral grains for which there is no known local source. Lead and S isotopic determinations were conducted to evaluate if the sulphide grains could have been transported from the nearest known source, the Pine Point Mississippi Valley-type district, or whether the grains are sourced from yet-to-be-discovered bedrock mineralization. Lead isotopic values from galena grains ($^{207}Pb/^{204}Pb$ = 15.57 to 15.70; $^{206}Pb/^{204}Pb$ = 18.00 to 18.20) indicate a more radiogenic source than the Pine Point district and are, therefore, likely to have been locally sourced. Sulphur isotopic values from galena grains range from 0 to 27‰ $\delta^{34}S$, comparable to Pine Point and other Mississippi Valley-type deposits globally, indicating that similar styles of mineralization may occur in the region. Chalcopyrite $\delta^{34}S$ values range from -22 to +28‰, indicating that the grains are sourced from either sediment-hosted Cu or Manto-style mineralization. Arsenopyrite $\delta^{34}S$ values indicate a sulphur source similar to orogenic gold deposits near Yellowknife, Northwest Territories, and are likely derived from the Canadian Shield, north of the study area.

INTRODUCTION

As part of the Northwest Territories Protected Area Strategy (PAS), several candidate areas, including the Sambaa K'e (Trout Lake region), Ka'a'gee Tu (Kakisa Lake region), and Lue Túé Sų̨lái (Jean Marie River region), were assessed for their potential to host economic bedrock mineralization (Fig. 1; Watson, 2011a,b, 2013). Part of the evaluation involved regional surficial till and stream sediment sampling surveys, which were conducted during the 2008, 2009, and 2012 field seasons (Watson, 2011a,b, 2013). Till samples from these surveys yielded encouraging results, with many samples containing high numbers of sphalerite, chalcopyrite, galena, and arsenopyrite grains, as well as some kimberlite indicator minerals (Watson, 2011a,b, 2013). The focus of this report is the picked base metal sulphide minerals (i.e. sphalerite, chalcopyrite, galena, and arsenopyrite) that were recovered during this initial evaluation. The data from these grains can assist in evaluating the potential for long-distance transport of sulphide grains from outside the immediate area (e.g. the Pine Point Mississippi Valley-type (MVT) district) and assist in evaluating the base metal mineral potential of the region. Preliminary in situ sulphur and lead isotopic analytical data of the sulphide grains are reported herein and are compared with previous studies.

LOCATION AND REGIONAL SETTING

The study area is located south of the headwaters of the Mackenzie River and extends from Hay River in the east to Liard River in the west (Fig. 1). Sampling was conducted over several field seasons, with work in the 2008 field season focused on NTS (National Topographic System) map sheets 95A (Trout Lake), with smaller sections of 95H (Fort Simpson), 95B (Fort Liard), and 85D (Kakisa River) (Fig. 2). Sampling during the 2009 field season was centred around NTS map sheet 85C (Tathlina Lake), with some sampling in 85D and 85F (Falaise Lake) (Fig. 2). Samples collected in 2012 were in NTS map sheet 95H.

Physiographically, this region is part of the Great Slave Plain and Alberta Plateau of the Interior Plains (Bostock, 1970). The Great Slave Plain contains abundant organic deposits and numerous small lakes and ponds, reflecting the poor drainage in the area due to the low relief (150–200 m). Areas classified as the Alberta Plateau occur in the southern portions of map sheets 95A, 85D, and 85C and are characterized by

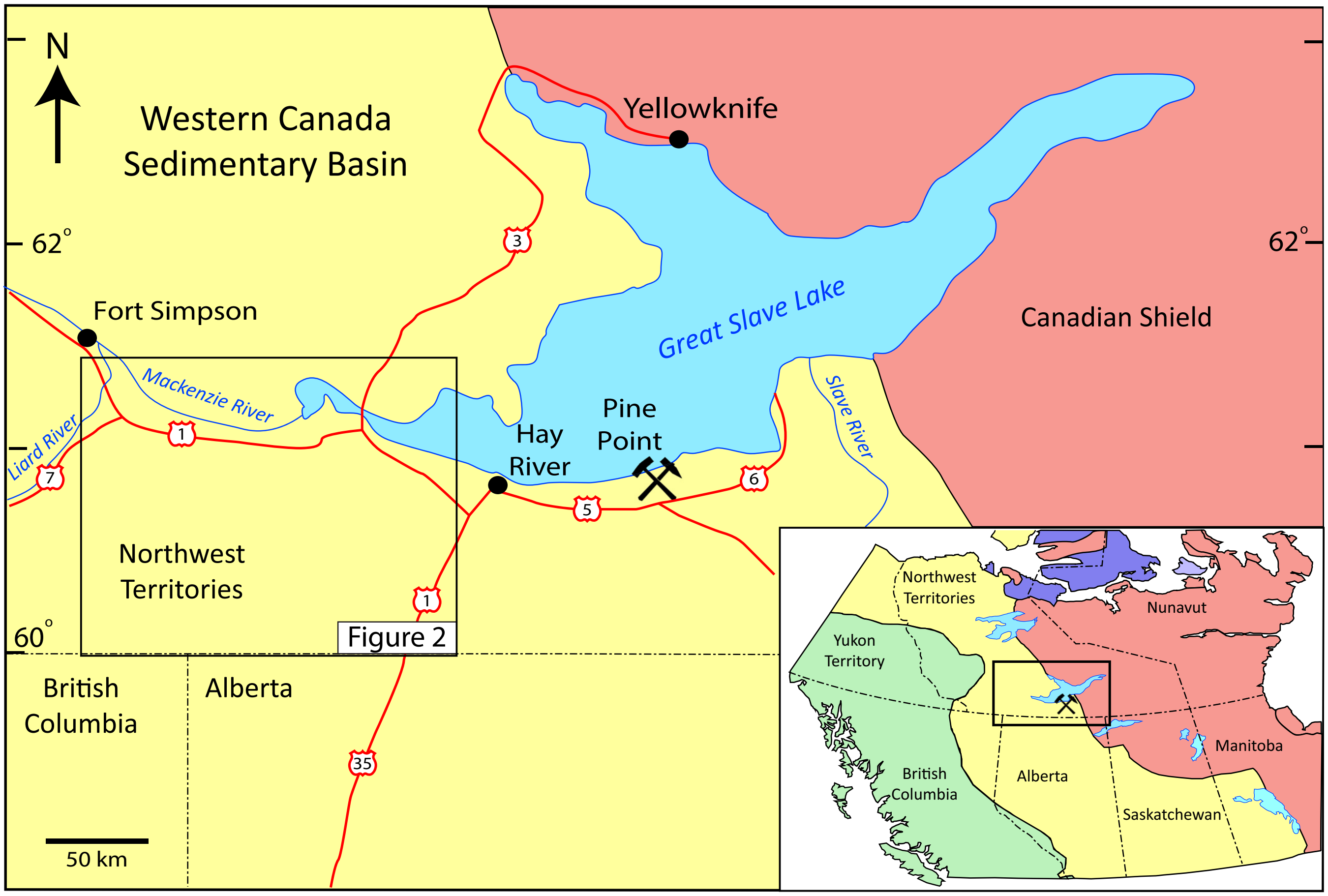

Figure 1. Location map of the study area in southwestern Northwest Territories, south of the Mackenzie River and east of the Liard River. Inset map shows the Canadian Shield (red), Western Canada Sedimentary Basin (yellow), and the Canadian Cordillera (green) (modified from Oviatt et al., 2015).

rolling hills and higher elevations (600–792 m). In addition to the numerous small lakes and ponds, several major lakes occur within the region, including Trout Lake in map sheet 95A, and Kakisa and Tathlina lakes in 85C.

REGIONAL GEOLOGY

Basement rocks in the region consist of Precambrian crystalline granite and gneiss. These are overlain by undated, pre-Devonian sandstone and clastic sedimentary rocks of the La Loche Formation, which were derived from the basement rocks (Meijer Drees, 1993; Gal, 2007). Overlying the La Loche Formation are Lower Devonian evaporite, shale, and dolostone (Meijer Drees, 1993; Gal, 2007). Middle Devonian rocks are predominantly platform carbonate, which locally form a distinct unit called the Presqu'ile reef-like barrier complex (Rhodes et al., 1984; Hannigan, 2006a). This barrier complex is formed by the Keg River, Sulphur Point, Watt Mountain, and Slave Point formations and is locally dolomitized, forming the Presqu'ile dolomite, which is coarse-grained and vuggy and hosts the Pine Point MVT district to the east (Rhodes et al., 1984; Hannigan, 2006a; Gal, 2007). Upper Devonian rocks conformably overly Middle Devonian strata and are composed of thick shale (up to 1.5 km), which are locally pyritic and bituminous, and are interbedded with reefal carbonate beds, especially in the lowest formation (Muskwa Formation) of the Upper Devonian sequence (Gal, 2007). The Upper Devonian Fort Simpson Formation locally hosts Manto-style Cu mineralization (Dudek, 1993; Watson, 2011a).

Conformably overlying the Devonian strata are Carboniferous limestone, shale, and sandstone, which are unconformably overlain by thin chert of the Permian Fantasque Formation. Shallow-dipping Cretaceous rocks dominate the southern map sheets (NTS 95A, 95B, and 85D; Fig. 2) and are subdivided into upper and lower Cretaceous units

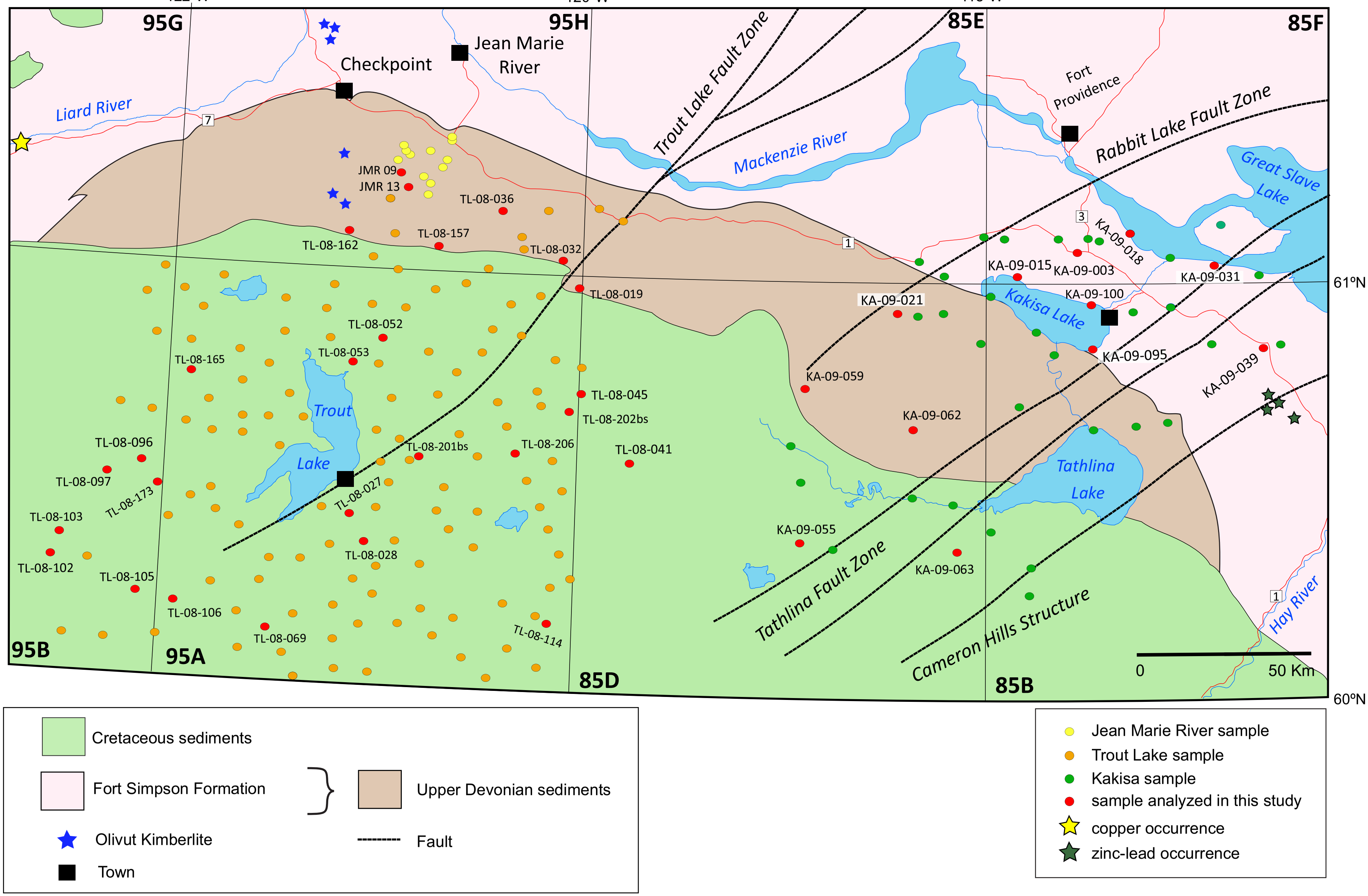

Figure 2. Simplified bedrock geological map (after Okulitch, 2006 and Bednarski, 2008) showing sample locations. The samples provided by the Northwest Territories Geological Survey are denoted by yellow, orange, and green circles (Watson, 2011a,b, 2013) and the samples analyzed in the present study are shown as red circles. The location of kimberlites is marked by blue stars (Pitman, 2014). Copper and Zn-Pb occurrences are indicated by yellow and dark green stars, respectively (Dudek, 1993; Paradis et al., 2006).

(Gal, 2007). Upper Cretaceous units in the region consist of interbedded conglomerate, sandstone, siltstone, and shale of the Dunvegan Formation and are restricted to highland regions northwest and southeast of Trout Lake (Gal, 2007). Lower Cretaceous units include the Fort St John Group shale, siltstone, and sandstone with local conglomerate (Gal, 2007; Berdnaski, 2008). Where present, Cretaceous units unconformably overly Paleozoic strata (Gal, 2007).

Surficial material in the region consists of muskeg, multiple tills, gravel, and sand, which is locally up to 25 metres thick (Fulton, 1995; Huntley et al., 2008). Several till units have been identified in the region. The lower till is blue-grey and clay-rich; it was either locally sourced or is an advance deposit from the Late Wisconsin Laurentide Ice Sheet (Huntley et al., 2008). An outwash unit separates the lower till units from the overlying, sandy, brown tills that represent lodgment and ablation tills or deformation tills and contain locally derived Devonian and Cretaceous siliciclastic and carbonate clasts and exotic igneous and metamorphic clasts, likely derived from the Canadian Shield (Huntley et al., 2008). Dominant ice flow during deglaciation in the Late Wisconsin was to the southwest, as indicated by numerous glacially streamlined features in the region that extend towards the Rocky Mountains and northeastern British Columbia (Huntley et al., 2008). Eastern parts of the map area were inundated by glacial Lake McConnell during deglaciation, which winnowed and reworked tills into glaciolacustrine littoral sediments (Lemmen, 1990).

PROTECTED AREA STRATEGY SURVEY SAMPLES

Sulphide mineral samples were provided by the Northwest Territories Geological Survey. Indicator mineral analysis of samples collected under previous Protected Area Strategy surveys (Watson, 2011a,b, 2013) recovered numerous sand-sized (0.25–2.0 mm) grains of sphalerite, galena, chalcopyrite, and arsenopyrite. Indicator mineral results reported here have been normalized to a 25 kg table feed weight for all samples. The number of normalized grains of each mineral species have been plotted on proportional circle diagrams (Fig. 3–6). Data breaks were arbitrarily assigned to control the large variations in the number sphalerite, galena, and chalcopyrite grains.

Sphalerite, which ranges in colour from red to orange to black, occurs in 22 samples from the Trout Lake region and in 35 samples from the Kakisa region, with the highest counts being 183 and 334 grains, respectively (Fig. 3). Chalcopyrite grains were picked from 133 samples from the Trout Lake region, with the highest count at 31 grains, 28 samples from the Kakisa region, with the highest count at 27 grains, and 2 samples from the Jean Marie River region, with the highest count at 30 grains (Fig. 4). Several of the samples containing sphalerite also contain varying amounts of galena, with the highest number of grains (28) occurring in a sample from the Trout Lake region (Fig. 5). Rare arsenopyrite grains were recovered only in Trout Lake samples, with the highest count being 3 grains (Fig. 6).

METHODS

Picked grains of sphalerite, arsenopyrite, chalcopyrite, and galena were mounted in 25 mm epoxy pucks and carbon coated prior to imaging on a JEOL JSM 7100F field emission gun (FEG) scanning electron microscope (SEM) equipped with a Thermo energy dispersive spectrometer (EDS) and a high-resolution silicon drift detector, at the Department of Earth Science, Memorial University of Newfoundland. Each grain was imaged using a 15.0 kV beam in backscatter (BED-C) and secondary electron (LED) mode. In addition to SEM imaging, each grain was analyzed at two points to determine the semi-quantitative chemical composition of the mineral grain and to ensure that the minerals were correctly identified during the optical identification and indicator mineral picking stages.

Epoxy mounted grains of sphalerite, galena, chalcopyrite, and arsenopyrite were polished and sputter coated with 300 Å of Au prior to analysis by the Cameca IMS 4f secondary ion mass spectrometer (SIMS) at the MAF-IIC Microanalysis Facility, Memorial University. Lead-isotope determinations were conducted on 6 galena grains (n=12) using a primary ion microbeam of 14 to 16 nA of O^-, accelerated through a nominal 10 keV potential, and focused into an ~20 μm diameter spot following the methods of Gill et al. (2015).

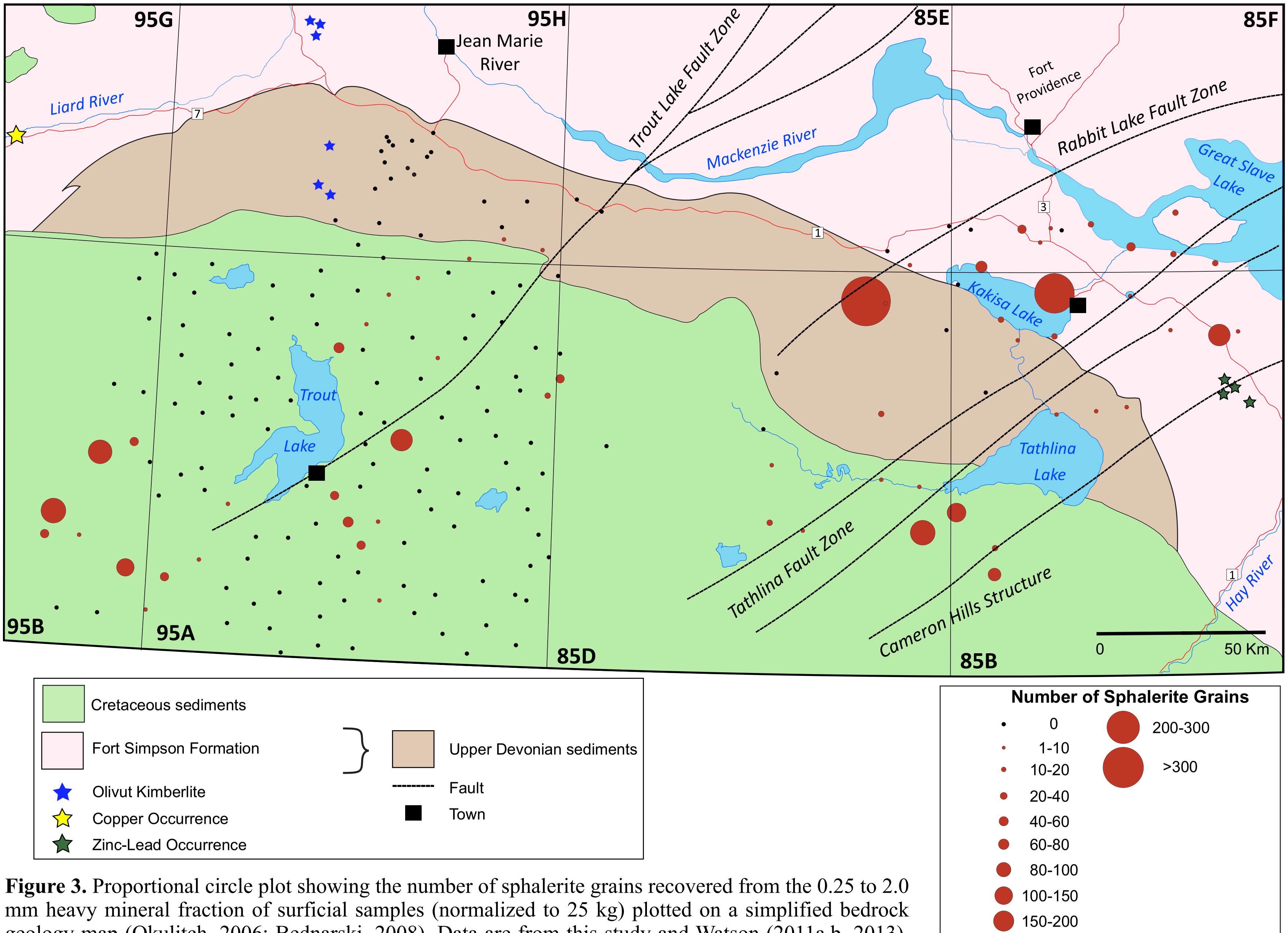

Figure 3. Proportional circle plot showing the number of sphalerite grains recovered from the 0.25 to 2.0 mm heavy mineral fraction of surficial samples (normalized to 25 kg) plotted on a simplified bedrock geology map (Okulitch, 2006; Bednarski, 2008). Data are from this study and Watson (2011a,b, 2013). Classification intervals were arbitrarily assigned to control the large variation in the number of grains.

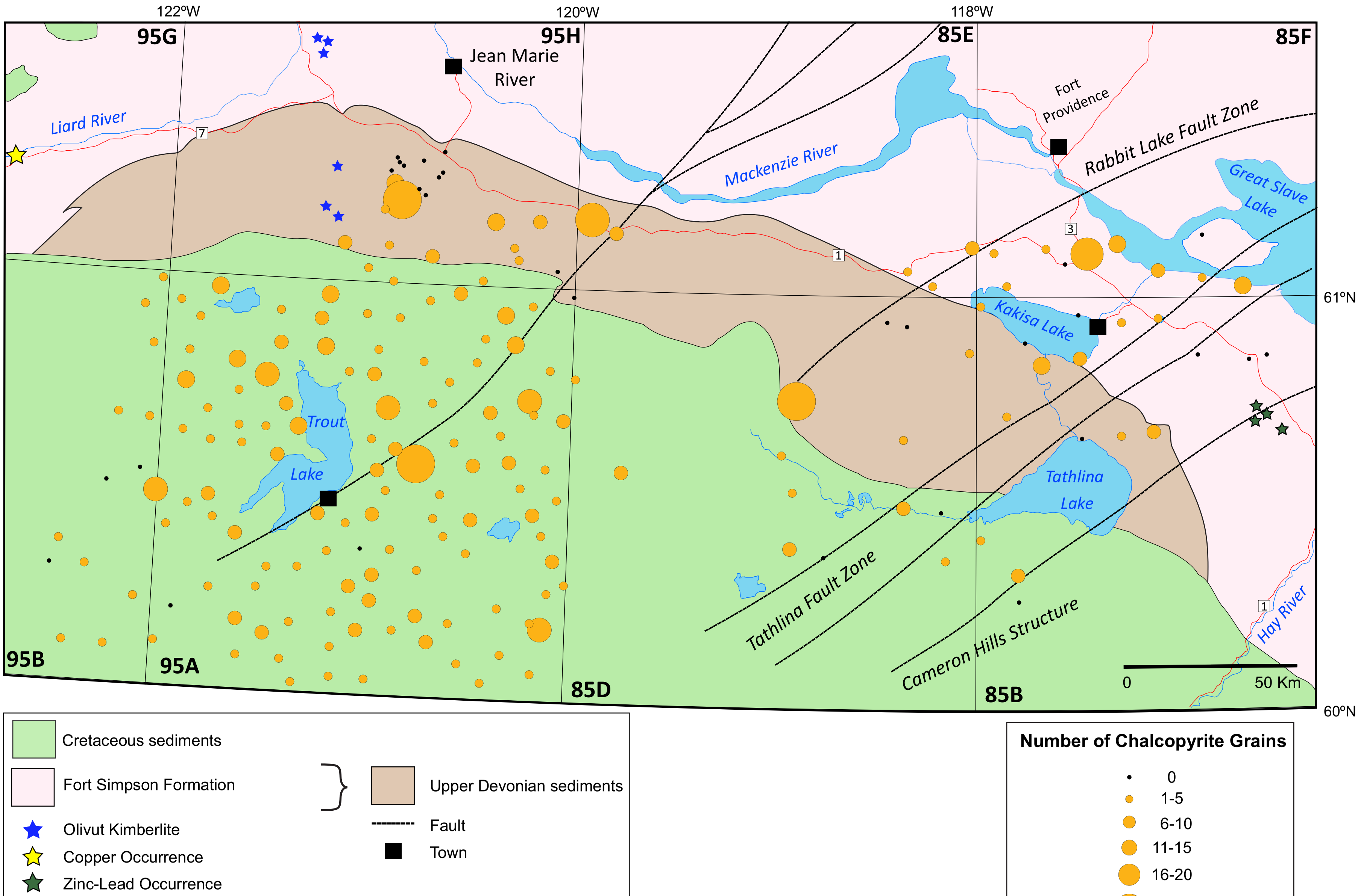

Figure 4. Proportional circle plot showing the number of chalcopyrite grains recovered from the 0.25 to 2.0 mm heavy mineral fraction of surficial samples (normalized to 25 kg) plotted on a simplified bedrock geology map (Okulitch, 2006; Bednarski, 2008). Classification intervals were arbitrarily assigned to control the large variation in the number of grains.

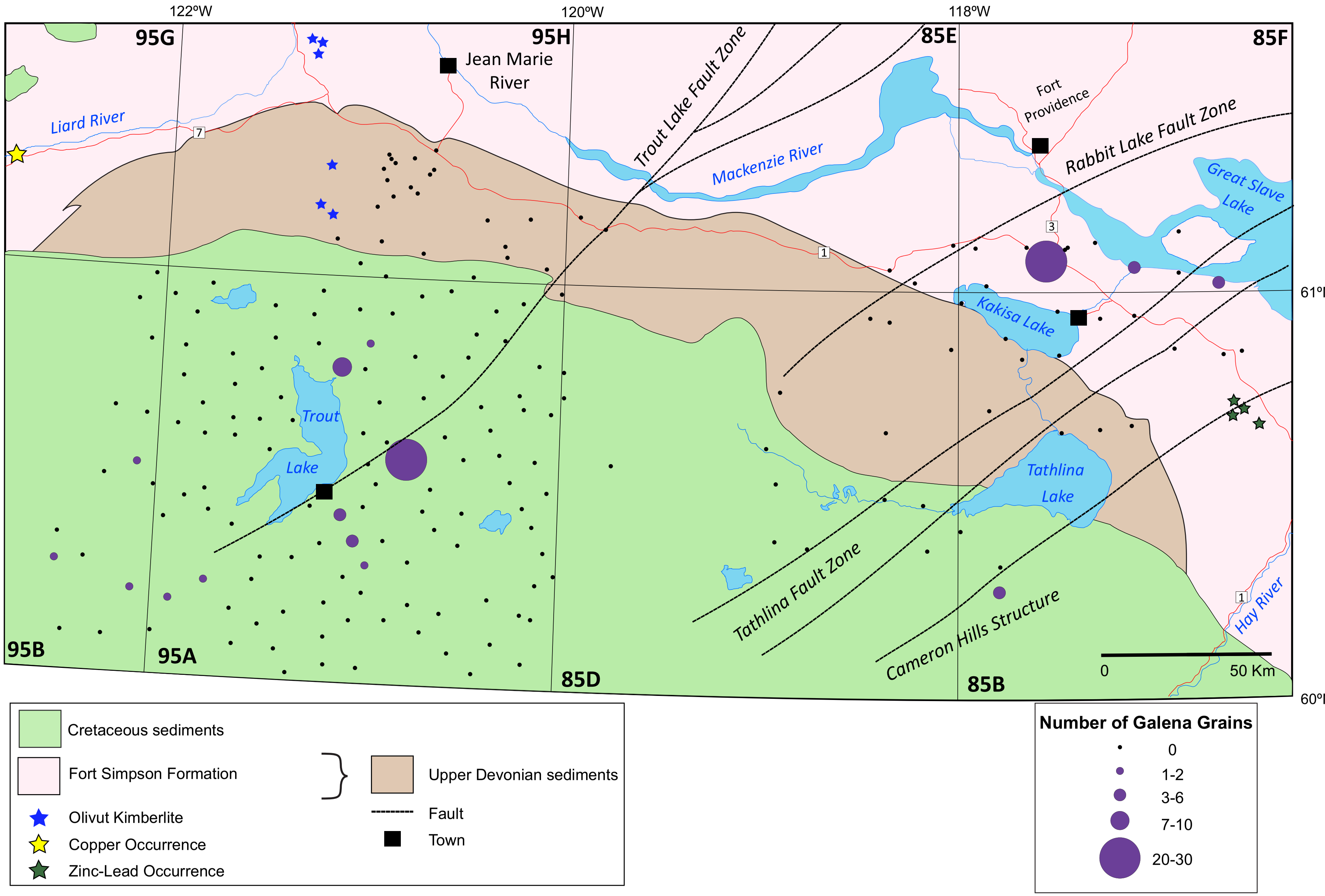

Figure 5. Proportional circle plot showing the number of galena grains recovered from the 0.25 to 2.0 mm heavy mineral fraction of surficial samples (normalized to 25 kg) plotted on a simplified bedrock geology map (Okulitch, 2006; Bednarski, 2008). Classification intervals were arbitrarily assigned to control the large variation in the number of grains.

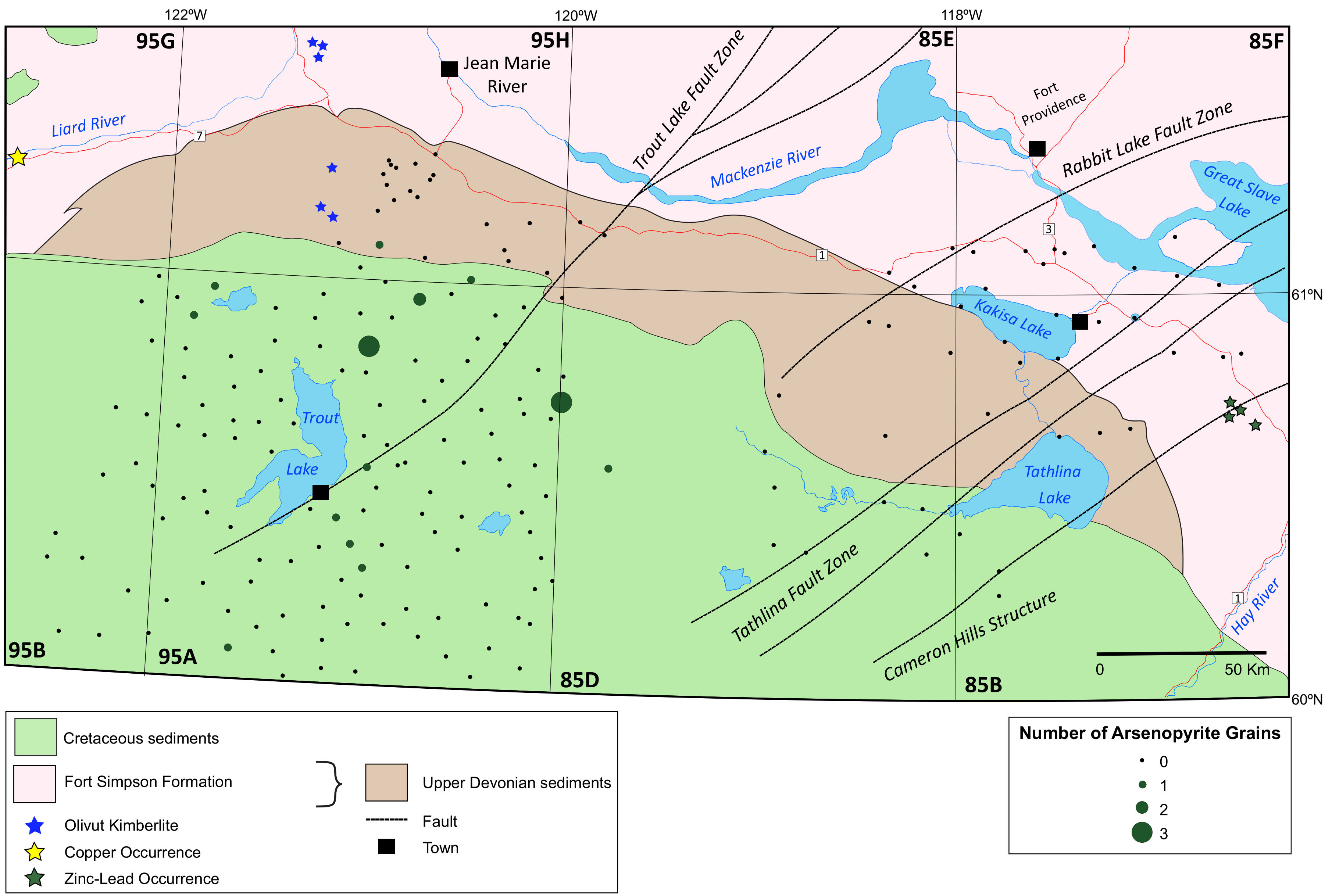

Figure 6. Proportional circle plot showing the number of arsenopyrite grains recovered from the 0.25 to 2.0 mm heavy mineral fraction of surficial samples (normalized to 25 kg) plotted on a simplified bedrock geology map (Okulitch, 2006; Bednarski, 2008).

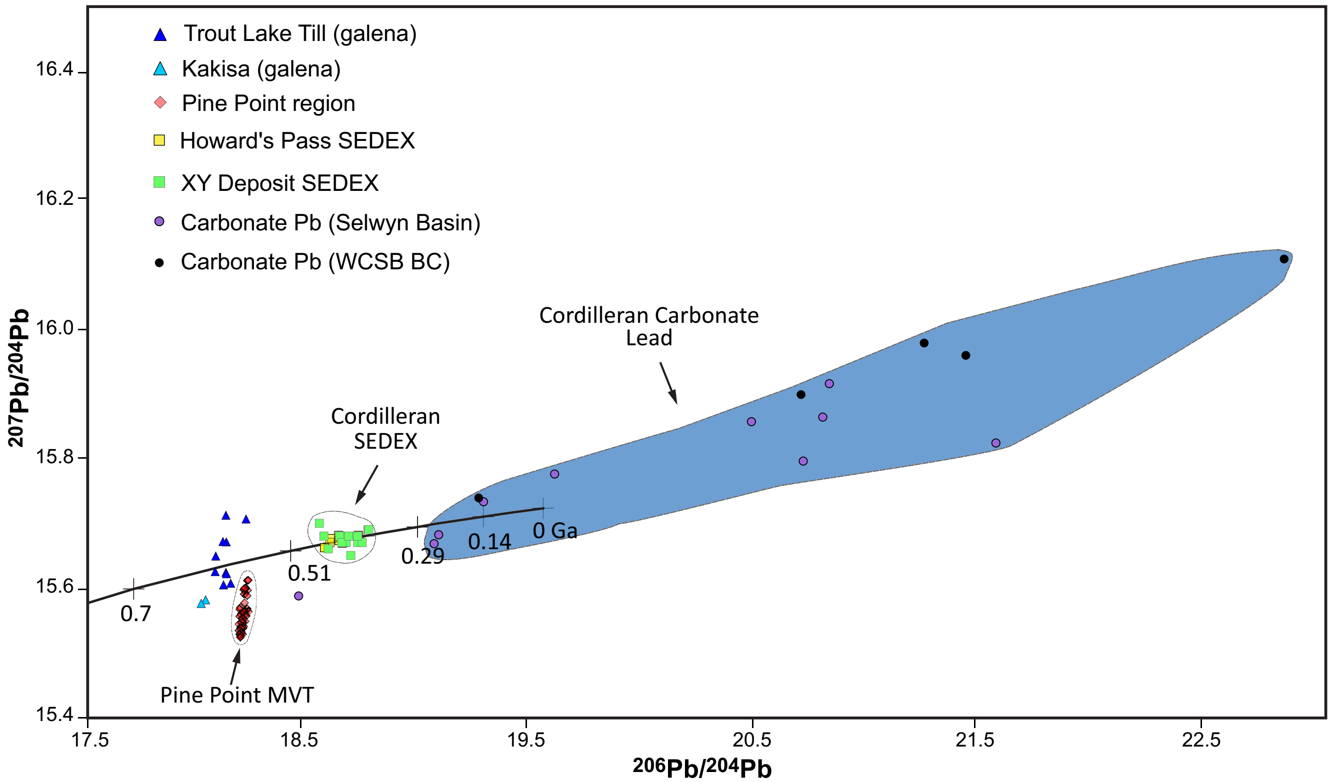

Figure 7. Lead isotope bivariate plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ for galena grains from the Trout Lake (dark blue triangles) and Kakisa (light blue triangles) regions (Appendix A). Shown for comparison are bedrock samples from Pine Point (pink diamonds; Cumming et al., 1990; Paradis et al., 2006; Oviatt et al., 2015). Data are plotted in reference to the shale curve of Godwin and Sinclair (1982). Also shown are data from other sedimentary exhalative (SEDEX) Pb-Zn deposits in Yukon and Mississippi Valley-type (MVT) deposits in northern British Columbia as well as values from the Western Canada Sedimentary Basin (Godwin et al., 1988; Paradis et al., 2006).

Sulphur-isotope determinations were carried out on 6 galena grains (n=7), 18 chalcopyrite grains (n=18), and 7 arsenopyrite grains (n=7) using a primary ion microbeam of 350–1150 pA of Cs+, accelerated by a 10 keV potential and focused into a 5–15 µm diameter spot following the methods of Brueckner et al. (2014). The Cs+ current depended on the sulphide phase analyzed. To prevent contamination of the polished surface, each spot was first pre-sputtered for 120 s with a 25 µm square raster. Negatively charged sputtered secondary ions were accelerated into the mass spectrometer using a potential of 4.5 keV. Sulphur isotope results are reported using per mil (‰) notation.

RESULTS

Lead isotope values for galena grains are listed in Appendix A and plotted in Figure 7. Results are plotted against the shale curve of Godwin and Sinclair (1982), a Pb-isotope growth curve unique to the Canadian Cordillera that was determined from Pb-isotopic compositions of galena from middle Proterozoic to Mississippian, sediment-hosted Zn-Pb deposits in the Cordillera. This curve is interpreted to reflect the upper continental crustal composition of the Cordilleran basement and western Laurentia. Several additional deposits and occurrences were plotted for comparison, including bedrock samples from the Pine Point District (Cumming et al., 1990; Paradis et al., 2006; Oviatt et al., 2015), and data for Pb-Zn deposits in the Canadian Cordillera and the Western Canada Sedimentary Basin (Godwin et al., 1988; Paradis et al., 2006).

Six galena grains were analyzed with 2 spot analyses per grain. Significant variations are observed among the grains with $^{206}Pb/^{204}Pb$ ratios ranging from 18.00 to 18.20 and $^{207}Pb/^{204}Pb$ ratios ranging from 15.58 to 15.71, with analyses clustering proximal to the shale curve, but with greater variation than mineralized samples from the Pine Point District (Fig. 7; Cumming et al.,

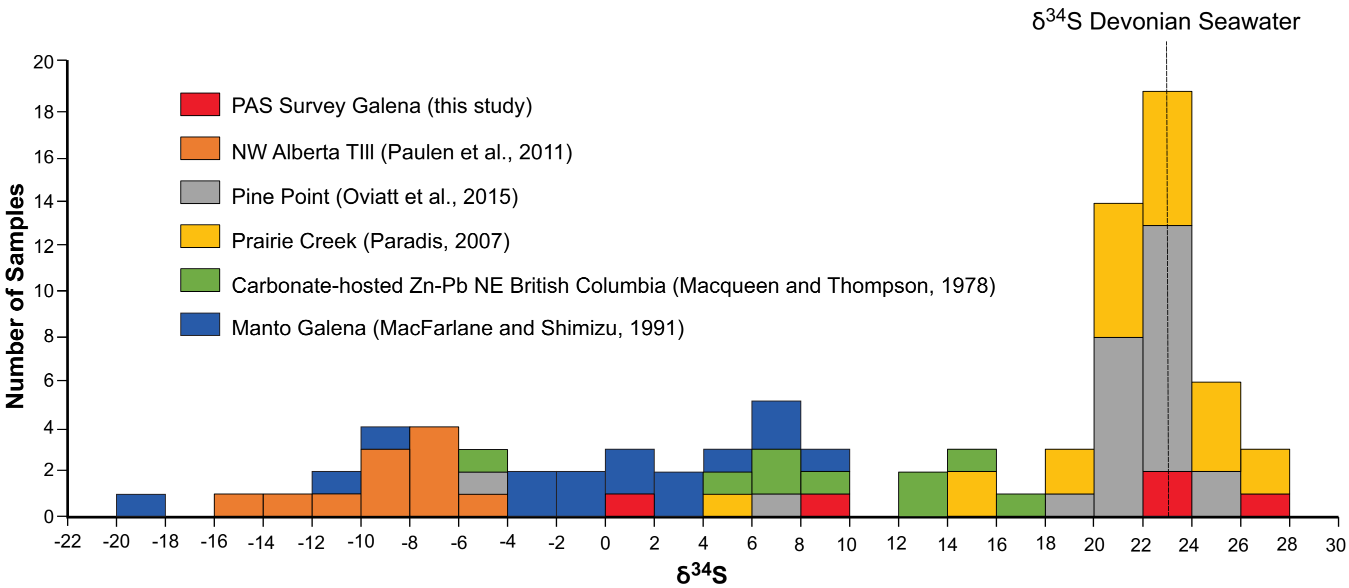

Figure 8. Histogram of $\delta^{34}S$ values of galena from samples collected in the Protected Area Strategy (PAS) survey (red: Appendix B) compared to values from till samples from northwestern Alberta (orange: Paulen et al., 2011), Pine Point (grey: Oviatt et al., 2015), Prairie Creek (yellow: Paradis, 2007), carbonate-hosted Pb-Zn in northeastern British Columbia (green: Macqueen and Thompson, 1978), and Manto-style mineralization in Peru (blue: MacFarlane and Shimizu, 1991).

1990). The $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios are typical of Pb derived from evolved upper crustal sources (e.g. Zartman and Doe, 1979; Zartman and Haines, 1988; Kramers and Tolstikhin, 1997). The distinctive array along an older isochron suggests that the galena grains from this study were from crustal sources but were likely older than the galena grains from the Pine Point District, or the fluids that formed galena grains in the region tapped separate, older, more radiogenic Pb sources compared to galena samples from Pine Point (Fig. 7; Cumming et al., 1990; Oviatt, 2013). The $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios for grains in this study and in samples from Pine Point plot above and below the shale curve are indicating that the Pb was derived from mixed, more radiogenic sources (Fig. 7).

Sulphur isotope data for the galena, arsenopyrite, and chalcopyrite grains are presented in Appendix B and plotted in Figures 8 to 10; sulphur isotope data for the sphalerite grains will be presented in a subsequent report. Galena $\delta^{34}S$ values are plotted along with values from a number of additional sources (Fig. 8): sphalerite in till samples from northwest Alberta (Paulen et al., 2011); sphalerite from bedrock and till around pit O-28 at Pine Point (Oviatt et al., 2015); pyrite, galena, and sphalerite from the Prairie Creek MVT and quartz-carbonate vein-hosted sulphide deposit (Paradis, 2007); sphalerite and galena from various MVT deposits in northeastern British Columbia, including Robb Lake, Mount Burden, and Nabesche River (Macqueen and Thompson, 1978); and galena from Manto-style Zn-Pb mineralization in Peru (MacFarlane and Shimizu, 1991). Samples of northwest Alberta (Paulen et al., 2011) and Pine Point (Oviatt et al., 2015) till were selected due their proximity to the Great Slave Lake Shear Zone (Eaton and Hope, 2003) and because they are known to contain some of the only significant bedrock mineralization in the region. The Prairie Creek MVT and vein-hosted sulphide deposits were selected because of their proximity to the study area and occurrence in the Cordillera, providing a good comparison for this study (Paradis, 2007), whereas MVT deposits and occurrences in northeastern British Columbia were chosen because they occur proximal to, and within the Presqu'ile barrier (Macqueen and Thompson, 1978). Manto-style Zn-Pb deposits in Peru were chosen because their mineralogy is similar to the known Manto occurrences in the Fort Simpson Formation (i.e. the presence of galena; MacFarlane and Shimizu, 1991).

The $\delta^{34}S$ values for chalcopyrite are plotted in Figure 9 against values from the Kamoto and

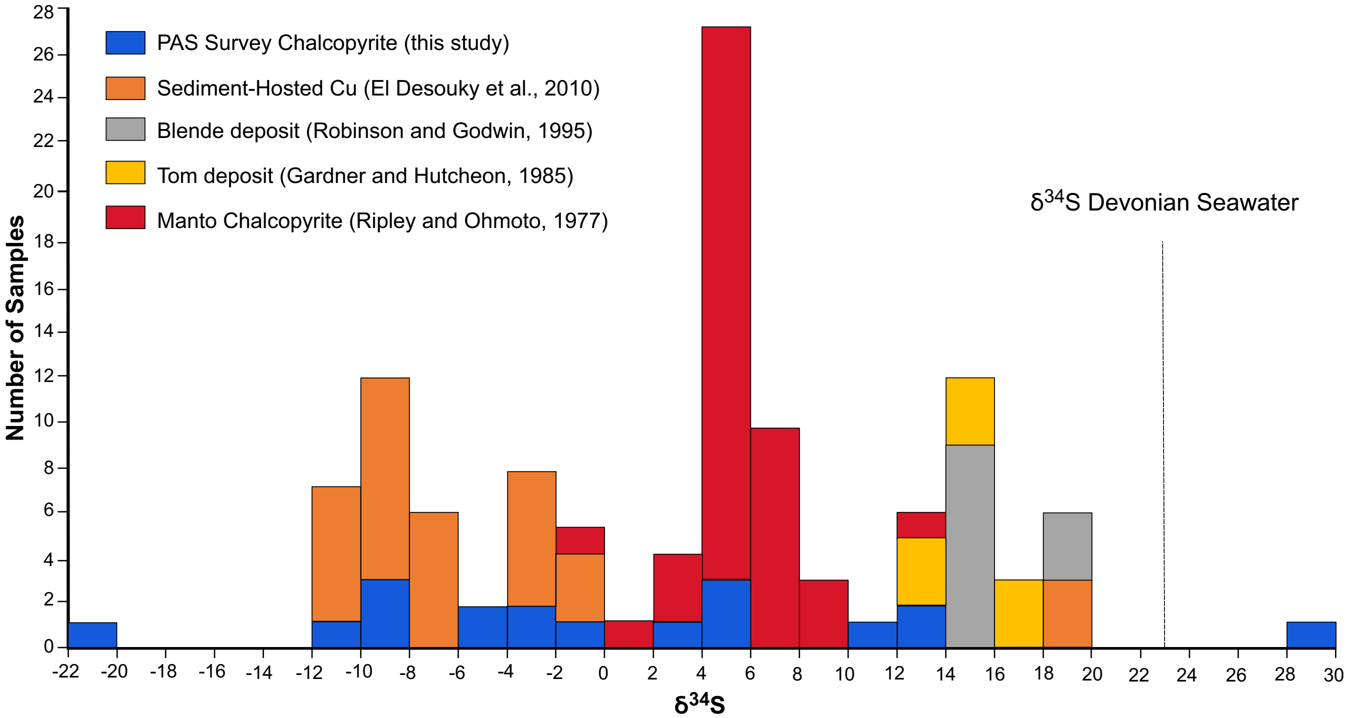

Figure 9. Histogram of $\delta^{34}S$ values of chalcopyrite grains from samples collected in the Protected Area Strategy (PAS) survey (blue: Appendix B) compared with values from sediment-hosted Cu deposits in Africa (orange: El Desouky et al., 2010); the Blende carbonate-hosted Pb-Zn deposit, Yukon (grey: Robinson and Godwin, 1995); the Tom sedimentary exhalative (SEDEX) deposit in the Yukon (yellow: Gardner and Hutcheon, 1985); and Manto-style mineralization in Peru (red: Ripley and Ohmoto, 1977).

Luiswishi sediment-hosted Cu deposits in Africa (El Desouky et al., 2010), carbonate-hosted Cu-bearing veins at the Blende deposit (Robinson and Godwin, 1995), Manto-style chalcopyrite mineralization in Peru (Ripley and Ohmoto, 1977), and chalcopyrite from the Tom SEDEX deposit (Gardner and Hutcheon, 1985). The $\delta^{34}S$ values from sediment-hosted Cu deposits in Africa were used as representative values for sediment-hosted Cu deposits globally, as no work on deposits of this type has been done in the study area, and because of the potential for similar styles of mineralization in the region (El Desouky et al., 2010). Carbonate-hosted Cu-bearing veins of the Blende deposit and Manto chalcopyrite mineralization in Peru was selected because of their mineralogy; the Tom SEDEX deposit was selected due to its occurrence in the Cordillera and the potential for SEDEX mineralization in the study region (Ripley and Ohmoto, 1977; Gardner and Hutcheon, 1985; Robinson and Godwin, 1995).

Arsenopyrite $\delta^{34}S$ values in Figure 10 are plotted against arsenopyrite $\delta^{34}S$ values from selected Canadian orogenic gold deposits (Giant Mine and Negus system; Wanless et al., 1960) and from sedimentary-hosted gold deposits (Meguma deposits; Kontak and Smith, 1989). $\delta^{34}S$ values from deposits occurring in the Yellowknife region were chosen because they occur up-ice from the samples collected in this study and they may be an analogue for expected $\delta^{34}S$ values from similar deposits up-ice of the region (Wanless et al., 1960). The sedimentary-rock-hosted Meguma gold deposits were selected because they contain arsenopyrite (Kontak and Smith, 1989).

The SIMS $\delta^{34}S$ values for galenas are consistent with values for sulphides (sphalerite and galena) from the Pine Point deposits, ranging from 0.73 to 26.87‰ (Fig. 8; Oviatt et al., 2015) and are generally more positive than $\delta^{34}S$ values of galena from Manto-style deposits (MacFarlane and Shimizu, 1991). Chalcopyrite has a wide range of $\delta^{34}S$ values (-20.64 to 28.33‰), similar to that for sediment-hosted Cu deposits in Africa as well as chalcopyrite from Manto deposits and associated disseminated sulphides in Peru (Fig. 9; Ripley and Ohmoto, 1977; El Desouky et al., 2010). Arsenopyrite $\delta^{34}S$ values range from -2‰ to 2‰, similar to values for igneous rocks (e.g. $\delta^{34}S = 0 \pm 3$‰; Ohmoto and Rye, 1979; Ohmoto and

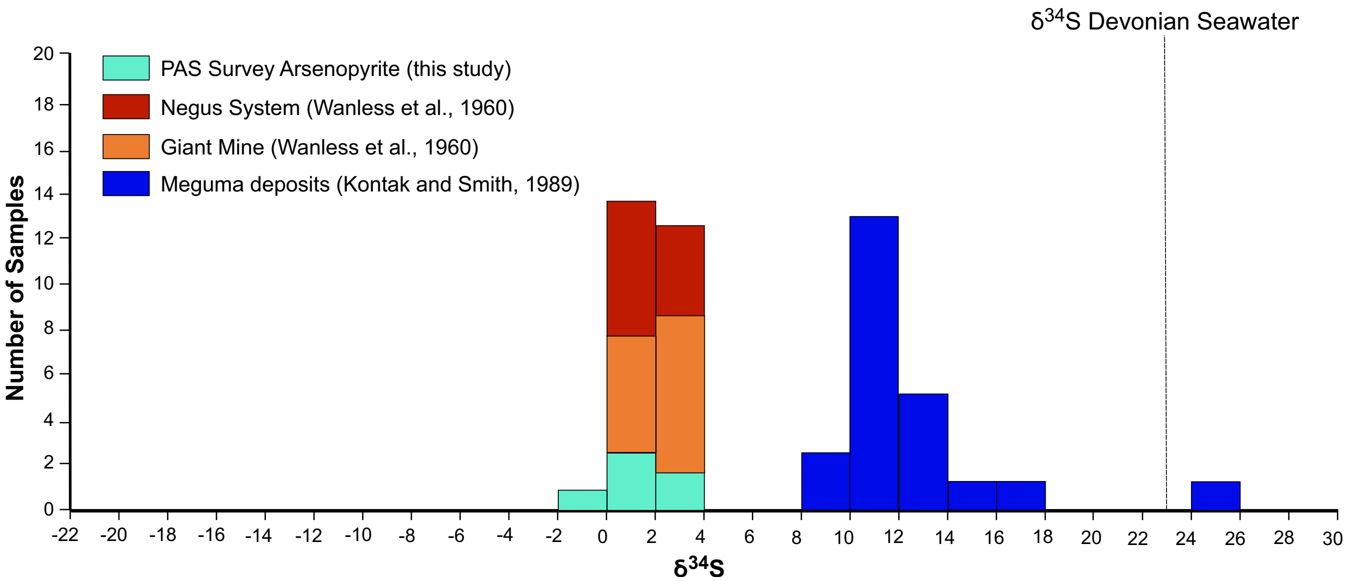

Figure 10. Histogram of $\delta^{34}S$ values of arsenopyrite grains from samples collected in the Protected Area Strategy (PAS) survey (teal: Appendix B) compared with values from the Negus system in the Northwest Territories (red: Wanless et al., 1960), the Giant gold mine in the Northwest Territories (orange: Wanless et al., 1960) and Meguma gold deposits in Nova Scotia (purple: Kontak and Smith, 1989).

Goldhaber, 1997). Such $\delta^{34}S$ values for arsenopyrite could indicate that sulphur in the arsenopyrite in the study area was derived from igneous basement rocks. However, it may also indicate that the arsenopyrite originated from orogenic veins, as arsenopyrite is a common accessory mineral in orogenic gold deposits and has similar sulphur isotope signatures to that of deposits near Yellowknife (Fig. 10; Wanless et al., 1960; Marini et al., 2011).

POTENTIAL EXPLORATION TARGETS

Very little follow-up work has been undertaken in the region to identify potential bedrock sources of sulphide grains in surficial materials. However, based on the similarity of the $\delta^{34}S$ values for galena grains from the study area to those from MVT deposits, the galena in the study area likely originated from MVT-style mineralization up-ice from where the samples were collected (e.g. Oviatt et al., 2015). Previous work in the Pine Point region by Oviatt (2013) showed that 700 m down-ice from mineralization, till samples generally contain tens of grains of galena, which is a reflection of the hardness of galena (2.5–3) and its brittle nature due to its cubic structure. Furthermore, galena rarely survives beyond transport distances of 1 km because of its susceptibility to disintegration during glacial transport. By analogy, it is assumed that the galena grains in the present study are locally sourced (i.e. likely less than 1 km from their source regions). As previously suggested by Hannigan (2006b), exploration should be focused in carbonate units proximal to the faults in the region, including the Trout Lake, Rabbit Lake, and Tathlina fault zones, as well as the Cameron Hills structure (Fig. 2). Chalcopyrite found in tills throughout the study area may have been sourced from sediment-hosted Cu mineralization, as indicated by the significant variations in $\delta^{34}S$ values, a feature found in sediment-hosted Cu deposits globally (Leblanc and Arnold, 1994; El Desouky et al., 2010). Alternatively, Manto deposits in Peru possess multiple mineralization styles, including vein- and sedimentary-hosted chalcopyrite, and though these are younger than mineralization in the study area, they have analogous chalcopyrite $\delta^{34}S$ values (e.g. Ripley and Ohmoto, 1977; MacFarlane and Shimizu, 1991); thus, Manto-type Cu may also be a potential target source for the chalcopyrite grains. Though the origin of the fluids and sulphur in Andean Manto deposits is debated (Barra et al., 2014), there is no current data for Manto targets in the region, thus requiring the use of global analogues; the latter should therefore be taken into consideration in any exploration of the area. The $\delta^{34}S$ signatures of arsenopyrite in till samples from this study fall within a range similar to that of arsenopyrite found in orogenic deposits near Yellowknife, approximately 380 km up-ice of the study area (Wheeler et al., 1996).

SUMMARY

A full interpretation of results, with additional data from picked sulphide indicator minerals recovered from a survey conducted in 2017 (Paulen et al., 2017; Day et al., 2018), will be presented in a later publication. The Pb and S isotopic compositions of galena grains recovered from till samples in the regions around Trout Lake and Kakisa Lake indicate that the grains were likely not dispersed from Pine Point but are from a proximal source within the study area. Similarly, the chalcopyrite, which is not noted as being present at Pine Point (Oviatt, 2013; Stanley Clemmer, Pine Point Mines, pers. comm., 2018), was found to have a wide range of $\delta^{34}S$ values, more akin to sediment-hosted Cu deposits (El Desouky et al., 2010); however, undiscovered Manto-style mineralization in the Fort Simpson Formation may present a potential source for chalcopyrite grains, as Manto-style mineralization and veins as well as disseminated sulphides at deposits in Peru have similar ranges of $\delta^{34}S$ values (Ripley and Ohmoto, 1977; MacFarlane and Shimizu, 1991). The $\delta^{34}S$ values for the arsenopyrite grains indicate an igneous source, either directly via magmatic fluids or via hydrothermal fluid leaching sulphur from igneous rocks. However, there is no known proximal, up-ice arsenopyrite source in the region, which presents an area requiring further investigation.

ACKNOWLEDGEMENTS

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