Preliminary observations on the volcanic rocks of the Keno-Mayo district (105M/13, 14), the Anvil district (105K/3, 6), and the MacMillan Pass district (105O/1, 2), central Yukon

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ABSTRACT

Over the past few years, the idea of volcanism being related to the formation of base-metal deposits, especially clastic sediment-hosted Zn-Pb (±Ag, ±Ba) deposits (sedimentary exhalative [SEDEX]), has been developing. During the 2016 field season, a study was initiated to test this hypothesis within the Selwyn basin, an area with known syngenetic deposits and numerous occurrences of volcanic rocks. Three districts were investigated. In the Keno-Mayo district, Ag-Pb-Zn vein deposits are hosted in the Carboniferous Keno Hill quartzite and may be related to Triassic intrusions. The quartzite is underlain by Devonian volcanic rocks of the Earn Group, which have unknown base-metal potential. In the Anvil district, the Cambrian to Ordovician Vangorda formation and lower Cambrian Mount Mye formation, which host the Zn-Pb-Ag-Ba SEDEX deposits, may be related to the volcanic rocks of the Ordovician to Silurian Menzie Creek formation. In the MacMillan Pass area, the Devonian Earn Group volcanic rocks are coeval with the formation of the Tom and Jason SEDEX deposits.

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INTRODUCTION

The North American western margin is a passive continental margin that developed during the Late Proterozoic to the Late Devonian (Goodfellow *et al.*, 1995). It includes the Selwyn basin, which comprises coarse clastic sediments, shale, siltstone and carbonate with alkalic volcanic rocks. The occurrence of volcanic rocks suggests rifting occurred intermittently within the Selwyn basin during the early Paleozoic. The periods of rifting were accompanied by alkalic and ultrapotassic volcanic and intrusive rocks that are distributed discontinuously along the entire continental margin (Goodfellow *et al.*, 1995; Cobbett, 2013). These magmatic rocks are spatially associated with clastic sediment-hosted Zn-Pb (±Ag, ±Ba) deposits (sedimentary exhalative [SEDEX]) and other deposit-types (*e.g.*, volcanic-hosted massive sulphide [VHMS], and polymetallic veins [*e.g.*, Keno Hill Pb-Zn-Ag veins]). However, despite spatial association of magmatic rocks to these deposit-types, genetic and temporal relationships remain unknown. The main objective of our study, which is supported by the Targeted Geoscience Initiative 5 (TGI-5) program of the Geological Survey of Canada, aims to resolve this matter using a combination of lithogeochemistry (major, trace, REE), radiogenic isotopes (Nd-Hf), U-Pb geochronology, petrographic analysis and mineral chemistry using the SEM and electron microprobe. During the summer of 2016, four weeks of preliminary field work was completed in the Keno-Mayo (105M/13, M/14), Anvil (105K/3, 6), and MacMillan Pass (105O/1, 2) areas of the Selwyn basin, central Yukon (Fig. 1). These three districts are host to Zn-Pb (±Ag, ±Ba) deposits (SEDEX, vein-type, and rare VHMS). The Anvil district hosts significant Zn-Pb-Ag-Ba SEDEX deposits (Faro, Vangorda, Swim, Grum and Dy), and one VHMS occurrence (Rebel). The Keno-Mayo district contains numerous Ag-Pb-Zn vein deposits (BelleKeno, Hector-Calumet, Lucky Queen and Elsa), and the MacMillan Pass district is well known for its Zn-Pb-Ag (±Ba) SEDEX deposits (Tom and Jason). This paper describes the lithology of rock units observed within the three districts with focus on the style of volcanism, and the samples collected for future geochemical, isotopic and geochronological studies.

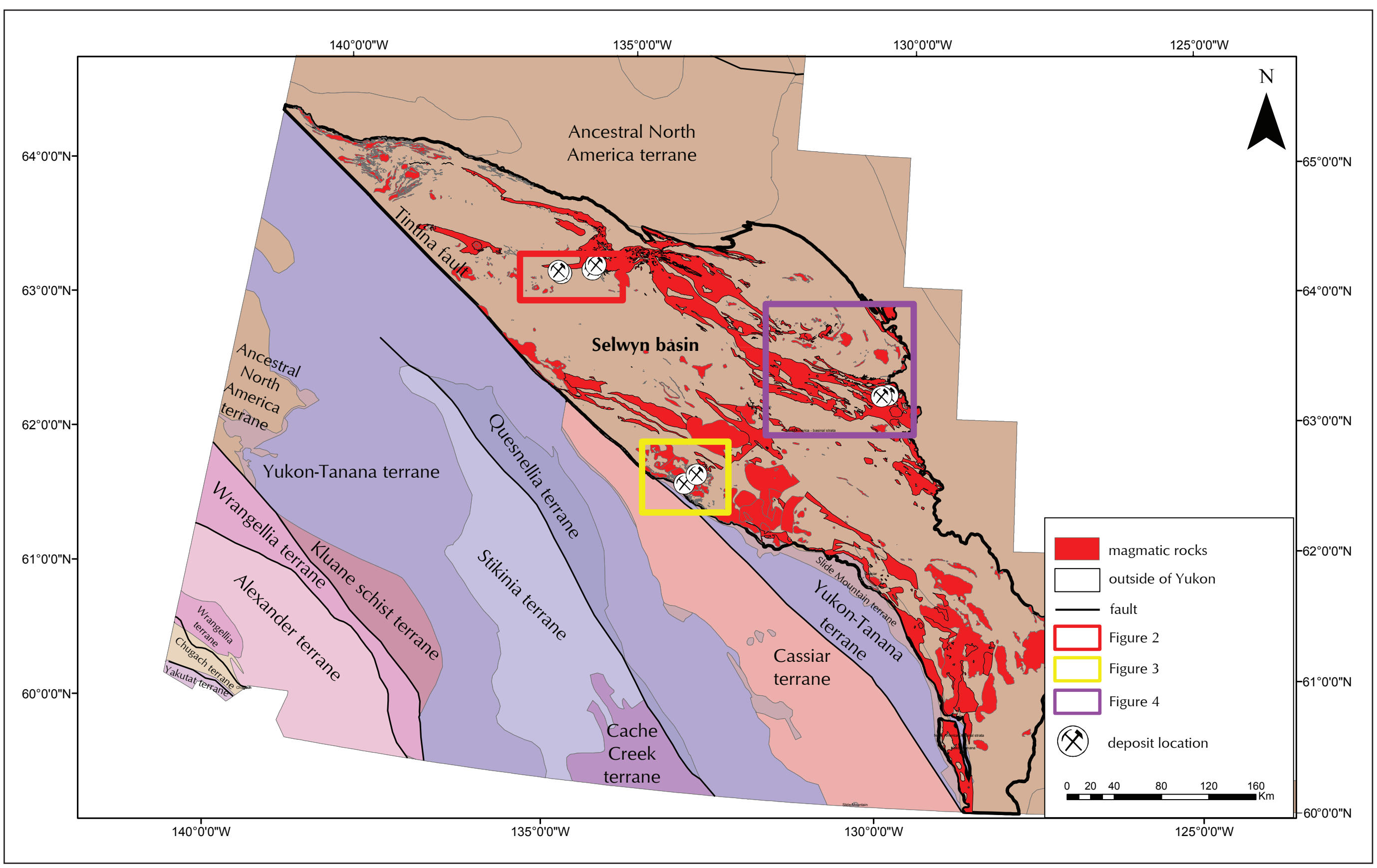


Figure 1. *Geologic map of the Selwyn basin, central Yukon and locations of study areas; modified from Colpron and Nelson (2011) .*

PRELIMINARY RESULTS

During the 2016 field season, 131 bedrock samples were collected from the Keno-Mayo district, the Anvil district, and the MacMillan Pass district for petrographic and geochemical analysis. Outcrops examined and samples collected in the Keno-Mayo district are from the Earn Group, Keno Hill quartzite, and Triassic intrusions. Rocks collected from the Anvil district are from the Vangorda formation, Menzie Creek formation, and the Earn Group. Samples collected from the MacMillan Pass area are from the Marmot and Niddery Lake volcanic rocks. Stratigraphic successions were observed within several localities in the Keno-Mayo (105M/13, 14), Anvil (105K/3, 6), and MacMillan Pass (105O/1, 2) map areas. The rock units were sampled to constrain the geology, document the styles of volcanism, and systematically sample the volcanic rocks for petrographic and analytical studies.

KENO–MAYO DISTRICT

The Keno-Mayo mining district in central Yukon is the second largest silver producer in Canada; mines operated from 1913 to 1989 on more than 65 Ag-Pb-Zn vein deposits hosted in the Keno Hill quartzite (Roots, 1997). These deposits post-date the ductile deformation of the Keno Hill quartzite (Roots, 1997). Volcanic rocks form a layer several metres to hundreds of metres thick at the top or near the top of the Devonian-Mississippian Earn Group (DMEV) strata (Fig 2a). Roots (1997) describes the metavolcanic rocks as foliated quartz-sericite-chlorite phyllite. Other rocks observed in the Earn Group are quartz-augen phyllite and minor carbonaceous phyllite interlayered with the metavolcanic rocks. The composition of the volcanic rocks suggests the presence of a regional-scale pyroclastic flow from a felsic dome or a laterally extensive submarine felsic flow (Roots, 1997). The Keno-Mayo district is rich in vein-style base metal deposits and contains volcanic rocks of the Earn Group that have unknown base-metal potential. The Keno Hill quartzite overlies the Earn Group in the northern part of the district (Fig. 2b). This unit is dominated by dark grey to black quartzite with minor phyllitic quartzite, chloritic and carbonaceous phyllite and metavolcanic rocks (Roots, 1997). Interpretation of depositional environment is difficult due to the lack, or obscuring of sedimentary features, although exposures in the Tombstone area (172 km WNW of Keno City) have non-marine fossils and are interpreted as indicating a shallow, well-aerated littoral environment (Roots, 1997). Triassic metadioritic and metagabbroic intrusive bodies crosscut the Earn Group and the Keno Hill quartzite (Fig. 2b). These intrusions are up to 50 m thick and 4 km long (Roots, 1997), and are exposed on the north-facing slope of Mount Haldane and around Keno Hill (Fig. 2a). The location of samples collected is shown in Figure 2a.

The Earn Group samples comprise greenish-white to green-grey quartz-sericite-chlorite phyllite and schist (Fig. 3a) inferred to be metavolcanic rocks, possibly metatuff and lapilli tuff. Chlorite commonly defines a foliation within the samples. Rare disseminated pyrite, along with feldspar and quartz microcrysts were observed in hand samples. In thin section, sample EG-20 appears to be sheared and contains approximately 5-10% sulphides and muscovite (Fig. 3b,c).

Samples collected from the Keno Hill quartzite are quartzite and phyllite. The quartzite samples are characterized by a coarse sugary texture and minor foliation (Fig. 3d). In thin section, sample KH-02 has sutured quartz grains, typical of the Keno Hill quartzite (Fig. 3e,f). Foliation is poorly developed in the quartzite and is defined by chlorite, pyrite ± phyllosilicates. Medium green-grey chlorite-quartz phyllite samples are both foliated and crenulated. Quartz and chlorite crystals are observed in thin section KH-04, with the chlorite crystals exhibiting crenulation cleavage (Fig. 3g,h). The phyllite samples were collected in an area previously mapped as Keno Hill quartzite but may be from the Earn Group.

The volcanic rocks and sediments are crosscut by fine to medium-grained Triassic metadiorite to metagabbro dikes (Fig. 3i). These intrusions are fine to medium-grained and contain quartz veins, disseminated pyrite, and galena that occur rarely in the hand sample (Fig. 3j) but are observed in thin section (Fig. 4k,l). These mafic intrusions commonly occur near mineralized veins of galena and chalcopyrite, and show a spatial relationship to the Ag-Pb-Zn mineralization; however, their temporal relationship is unknown because the exact age of the Ag-Pb-Zn veins has not been determined.

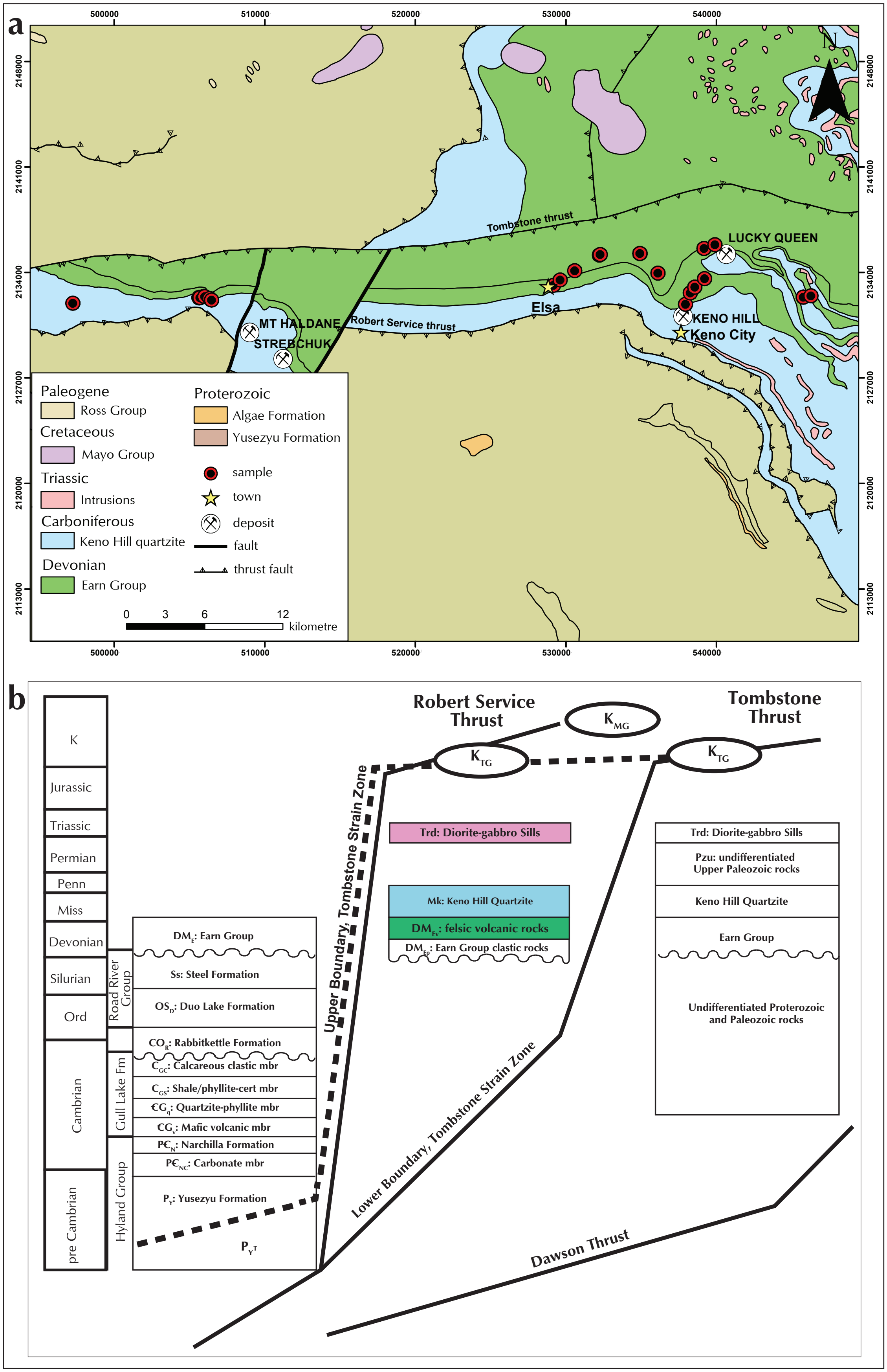


Figure 2. (a) *Geologic map from the Keno-Mayo district and sample locations; from Yukon Geological Survey 2016.* ***(b)*** *Stratigraphic column of the Keno-Mayo district; modified from Murphy and Roots (1996).*

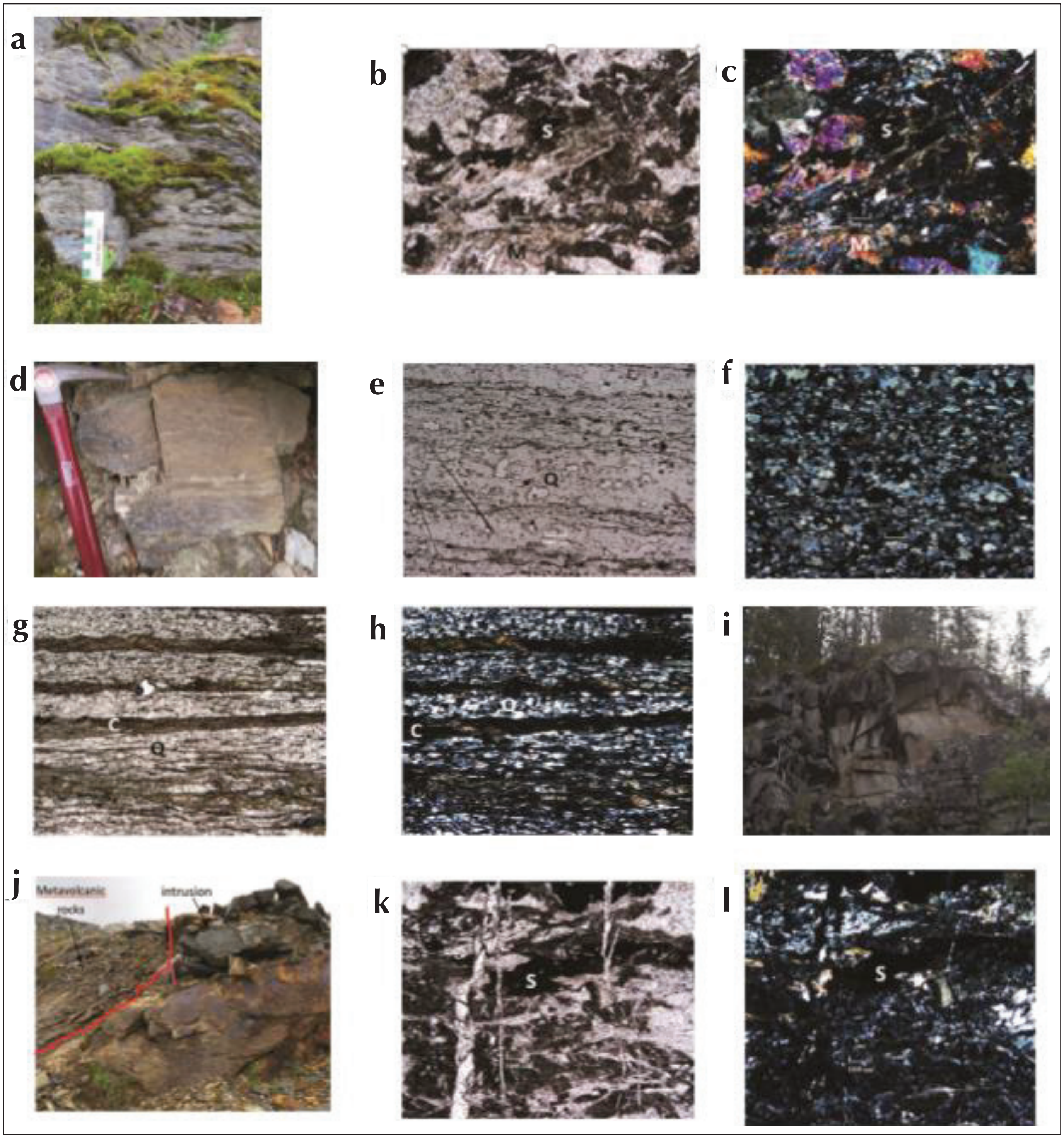


Figure 3. (a) *Greenish to green-grey quartz-sericite-chlorite schist inferred to be felsic metavolcanic rocks, Devonian-Mississippian Earn Group. Outcrop ~1 km east of Elsa.* ***(b)*** *Sample EG-20 - dike with 5-10% sulphides (S) and phenocrysts of muscovite (M) at 5x magnification in plane-polarized light.* ***(c)*** *Sample EG-20 in cross-polars.* ***(d)*** *Angular blocky Mississippian Keno Hill quartzite.* ***(e)*** *Sample KH-02 - quartzite with sutured quartz grains (Q) and minor amounts of biotite, defining the foliation. 5x magnification in plane-polarized light.* ***(f)*** *Sample KH-02 in cross-polars.* ***(g)*** *Sample KH-04 - phyllite with stretched quartz grains (Q) and chlorite (C) defining the foliation, and a well-defined crenulation cleavage (5x plane-polarized light).* ***(h)*** *Sample KH-04 in cross-polars.* ***(i)*** *Metavolcanic rocks are crosscut by a medium-grained Triassic intrusion (red line denoting the contact).* ***(j)*** *Fine-grained Triassic mafic intrusion in outcrop east of Elsa.* ***(k)*** *Sample TI-07 is a medium-grained dike with sulphides (S) and minor quartz, biotite, glass and quartz veins also visible. 5x magnification plane-polarized light.* ***(l)*** *Sample TI-07 in cross-polars.*

ANVIL DISTRICT

The Anvil district (Fig. 4a) is the largest Zn-Pb mining camp in northwestern Canada with estimated geological reserves (before mining) of 120 million tonnes at a combined Pb+Zn grade of 9.3% (Jennings and Jilson, 1986). The district contains five known/documented Zn-Pb-Ag-Ba SEDEX deposits (Faro, Vangorda, Swim, Grum, and Dy; Carne and Cathro, 1982), which occur in a 150 m stratigraphic interval straddling the contact between the metasedimentary lower Cambrian Mount Mye (equivalent Gull Lake Formation) and Cambrian to Ordovician Vangorda (equivalent Rabbitkettle Formation) formations (Fig. 4b). Ordovician Menzie Creek volcanic rocks (OSM) host VHMS and minor base-metal deposits. The Menzie Creek volcanic rocks are intercalated with black shale and phyllite of the Duo Lake Formation (Road River Group), which host the Howards Pass SEDEX deposit, meaning there could be other large SEDEX deposits of this age that have yet to be found. The Vangorda formation is dominated by fine-grained calc-silicate schist and hornfels (Cobbett, 2013). These rocks are interpreted to be bedded carbonate that went through regional metamorphism that was then overprinted by contact metamorphism (Pigage, 2006; Cobbett, 2013). A thick, resistant, grey-weathering, succession of volcanic and volcaniclastic rocks, named the Menzie Creek formation (Jennings and Jilson, 1986), conformably overlies the Vangorda formation. The Menzie Creek volcanic rocks, which host the Rebel VHMS occurrence (Yukon MINFILE 105K 083) and other potential VHMS deposits, outcrop south and north of the Anvil Batholith (Fig. 4a) ~20 to 25 km from Anvil Mine. Geochemistry reported by Pigage (2006), indicates that most of the volcanic rocks are alkaline basalt with a within-plate tectonic affinity. Depositional textures seen in outcrops and hand samples indicate submarine volcanism (Pigage, 2006). The Earn Group is exposed in the northern part of the Anvil district and is structurally overlain by the Menzie Creek formation. Here the Earn Group is dominated by carbonaceous phyllite, metatuff, and chert with lesser quartzite and chert-pebble conglomerate (Pigage, 2006; Cobbett, 2016). These units are exposed around the Faro area and to the north of the Anvil Batholith (Fig. 4a).

In the Anvil district, samples were collected from the Vangorda formation, Menzie Creek formation, and the Earn Group. The sample collected from the Vangorda formation, south of the Anvil Batholith, near the contact with a gabbro is a fine-grained silver-grey phyllitic schist, with foliation defined by alignment of phyllosilicate minerals that parallel the quartz veins. A sample of chert collected south of the batholith contains rare large quartz veins and epidote.

The Menzie Creek volcanic breccia contains basalt fragments of various sizes (1-3 cm) that are variably altered with a silicified matrix (Fig. 5a). Much of the breccia is oxidized and mineralized (Fig. 5b). The basalt flows of the Menzie Creek formation are amygdaloidal, and occur as both massive and pillowed flows. Basalt south of the batholith is more deformed and altered (Fig. 5c) than that north of the batholith where the basalt exhibits primary textures (Fig. 5d). In thin section, the basalt is fine-grained and contains glass fragments (Fig. 5e,f). Samples of tuff are mafic (Fig. 5g) and contain some stretched lithic clasts. Flow top breccia is about 20 cm thick, fine grained and overlain by altered quartzite.

Ordovician-Silurian gabbro and pyroxenite intrusions crosscut the Mount Mye, Vangorda, and Menzie Creek formations. The gabbro south of the batholith is fine grained with acicular matrix and appears to be sheared. North of the batholith, the gabbro is fine grained and contains 2-3 mm pyroxene crystals. Some samples have rare chloritic spots (Fig. 5h). The pyroxenite south and north of the batholith is dark brown-green, fine-grained, massive, and undeformed (Fig. 5i).

Samples of metatuff were collected from the Earn Group north of the Anvil Batholith. The samples are quartz-rich with chlorite and feldspar fragments. The metatuff sampled is on average 10 m thick and overlain by a 1 to 10-m-thick shale bed. The tuff is locally interbedded with fine-grained fissile shale (Fig. 5j).

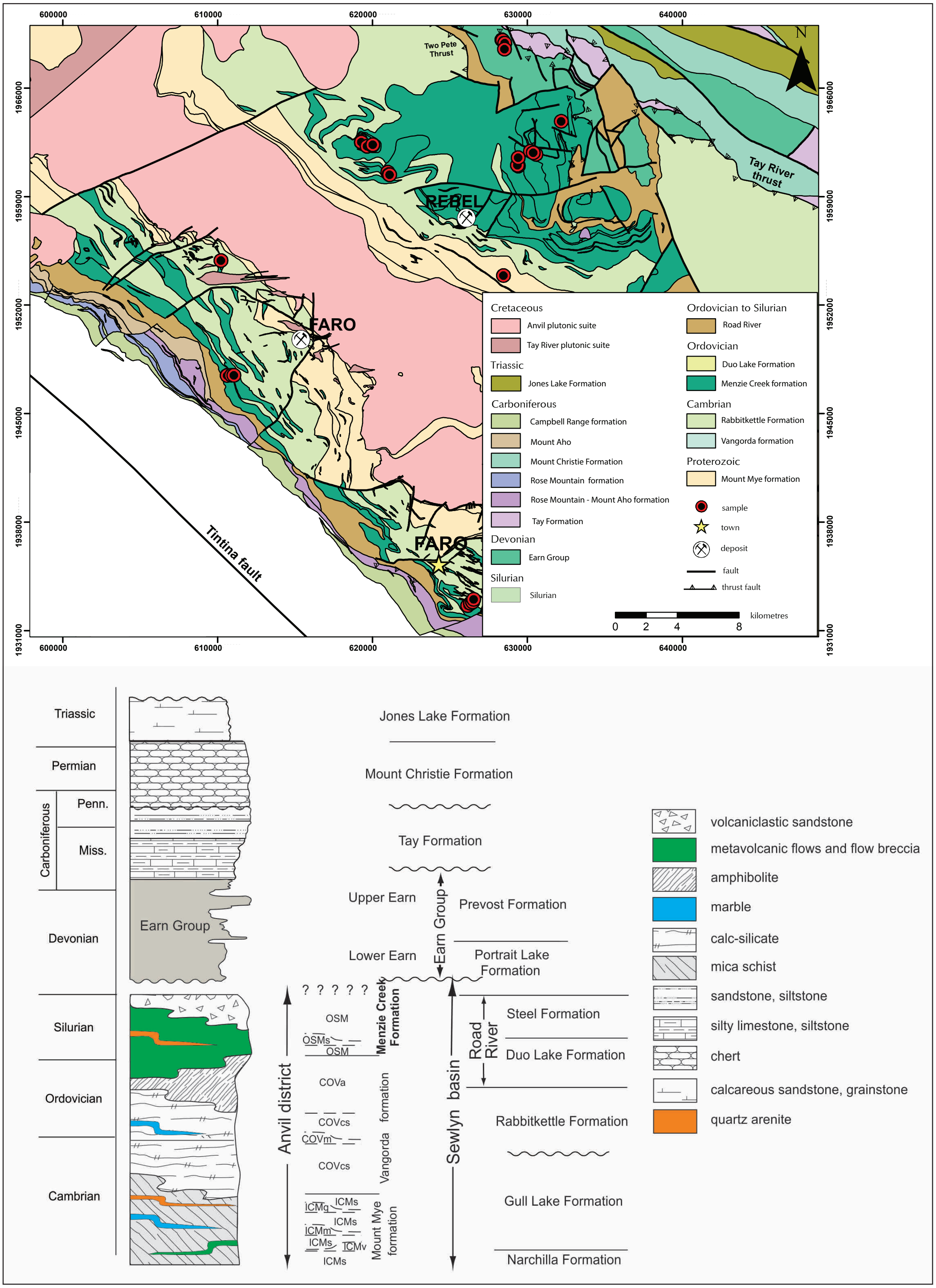


Figure 4. (a)*Geologic map from the Anvil district and sample locations; modified from Yukon Geological Survey, 2016.* ***(b)*** *Stratigraphic column of the Anvil district; modified from Cobbett (2013).*

Figure 5. (a) *Menzie Creek formation, clast-supported monolithic, basalt breccia. Note: highly scoriaceous fragment in the middle of the photo.* ***(b)*** *In situ breccia with fractures filled by oxidized sulphides and chlorite, Menzie Creek formation, north of the Anvil Batholith.* ***(c)*** *Deformed and altered pillow basalt flow of the Menzie Creek formation, south of the Anvil Batholith.* ***(d)*** *Stretched pillow basalt, Menzie Creek formation, north of the Anvil Batholith.* ***(e)*** *Very fine grained basalt with an aphanitic texture and glass fragments at 5x magnification.* ***(f)*** *Crossed-polars.* ***(g)*** *Sheared mafic tuff, Menzie Creek formation, north of the Anvil Batholith.* ***(h)*** *Medium-grained gabbro, Menzie Creek formation, south of the Anvil Batholith.* ***(i)*** *Pyroxenite north of the Anvil batholith, Menzie Creek formation.* ***(j)*** *Earn Group tuff interbedded with fine-grained shale.*

MACMILLAN PASS DISTRICT

All known SEDEX deposits of the MacMillan Pass district are hosted within the clastic sediment of the middle to upper Devonian Portrait Lake Formation of the Lower Earn Group, and they occur adjacent to NE-trending extensional synsedimentary faults (Fig. 6a). The volcanic rocks form thin lenticular belts that are commonly associated with feeder dikes and sills (Goodfellow *et al.*, 1995). The MacMillan volcanic rocks (Dv; Earn Group; Fig. 6a) are discontinuous Devonian aged tuff, volcaniclastic rocks, and minor flows (Cecile and Abbott, 1992; Fig 6b). West of the Jason deposit, volcanic diamictite is interbedded with Pb-Zn sulphides giving an obvious genetic and temporal relationship. The Devonian Niddery Lake volcanic rocks (D_N; Fig. 6b) comprise basalt, tuff, volcaniclastic sandstone, siltstone and mudstone with minor tuff, shale, and limestone (Goodfellow *et al.*, 1995). These rocks directly overlie, and are interstratified with, Cambrian argillite (Hofmann and Cecile, 1981; Cecile and Abbott, 1992). According to Goodfellow *et al.* (1995), the volcanic rocks are temporally associated with the formation of the Tom, Jason, and Boundary Creek SEDEX deposits, and are spatially associated with the Boundary Creek and Jason deposits. Samples collected from the MacMillan Pass area come from two predominant volcanic complexes, the MacMillan and the Niddery Lake volcanic rocks (Fig. 6a). Volcanic rocks previously mapped as Marmot Formation in the district were also collected.

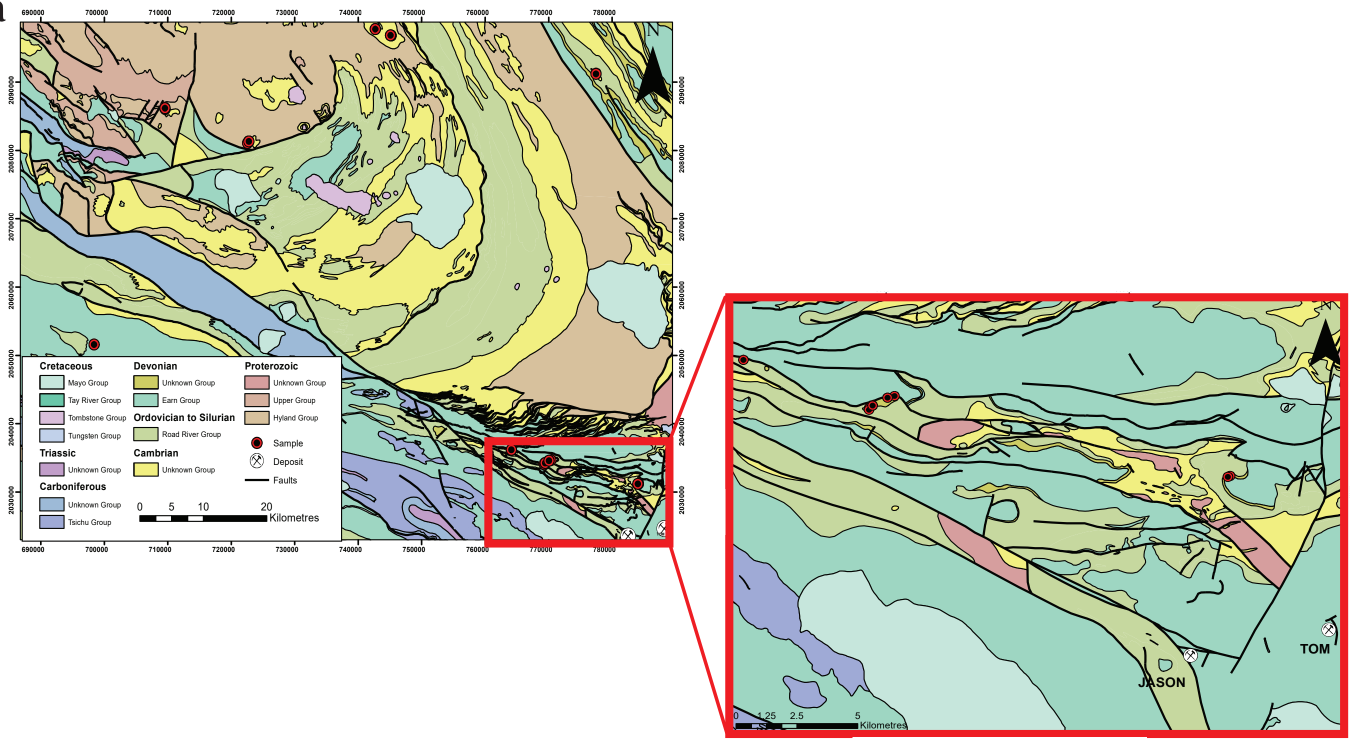
The MacMillan volcanic rocks were sampled from orange weathering, carbonate-rich tuff, mafic volcanic flows(?), gabbroic sills and dikes, and a variety of volcanoclastic breccia. The tuff (Fig. 7a) has quartz phenocrysts, is clast-rich (some with reaction rims), and has a silicified matrix (Fig. 7b,c), suggesting that it is felsic in composition. The mafic volcanic rocks are light-grey and fine grained. These samples are columnar jointed in outcrops (Fig. 7d). The gabbroic sills and dikes are fine to medium grained with rare quartz-filled amygdales. The breccia is clast and matrix-supported, and tan in color due to the silicified nature of the matrix. It includes 1 to 3 cm angular to subangular clasts.

The Niddery volcanic samples include scoria fragments from within flows, volcanic breccia, tuff, intrusive rocks, and flow top breccia. The scoria fragments collected from the volcanic flows are mafic in composition, typically red with large (4 mm) vesicles (Fig. 7e), filled with quartz (Fig. 7f,g). The breccia samples have a fine-grained matrix and are clast-supported (Fig. 7h). The fragments are typically scoria or chert. Sedimentary rocks in contact with the volcanic rocks are sandstone and chert, which show a fining upward succession. The tuff samples are fine grained with red-orange oxidation. Some samples have quartz veinlets and chlorite crystals. The intrusive rocks include a felsic dike and gabbro. The felsic dike is fine grained and contains quartz veins. The dark green-grey gabbro crosscuts the breccia and is coarse grained with large epidote crystals. The flow top breccia sample is mafic with vesicles up to ~2 cm in size and contains some scoria and shale fragments.

DISCUSSION

SEDEX deposits form due to the upflow of fluids controlled by synsedimentary faults, driven by geopressure release, seismic pumping, or deep convection cells (Lydon, 2004). The ore fluids are generated from formational waters of the sedimentary basins that become hot, saline, and metalliferous (Leach *et al.*, 2005; Leach *et al.*, 2010; Wilkinson, 2014). Previous studies (*e.g.*, Goodfellow *et al.*, 1995; Lydon, 2004; McCusker and Reed, 2013) suggest relationships between volcanic rocks/magmatic rocks and SEDEX deposits in the Selwyn basin. In British Columbia, the Sullivan deposit is a good example of a SEDEX deposit that formed with the involvement of magmatic rocks. The emplacement of thick gabbroic sills into wet unconsolidated sediments caused mud volcanoes to form, which formational brines used as conduits resulting in sulphide mineralization (Lydon, 2004). The emplacement of the sills caused the temperature of the fluids at the margins to reach 600°C, driving the ascent of hydrothermal fluids (Lydon, 2004). The Irish-type deposits are also associated with magmatism in places. The migration of fluids in Irish-type deposits is typically controlled by normal faulting, but in some deposits, there appears to be a spatial relationship to volcanism. For example, at the Stonepark deposit in Ireland, there is no normal fault along which fluids could have migrated. McCusker and Reed (2013) suggest that the intrusive rocks provide a pathway that transported the ore fluids to the black matrix breccia zone, which hosts the mineralization.

This study investigates the potential for relationships (spatial, temporal and genetic) with volcanism and clastic sediment-hosted Zn-Pb (±Ag, ±Ba) deposits (~sedimentary exhalative [SEDEX]) in the Selwyn basin (Goodfellow *et al.*, 1995), specifically in the Early Cambrian Anvil district, the Late Devonian MacMillan Pass district, the Late Devonian a



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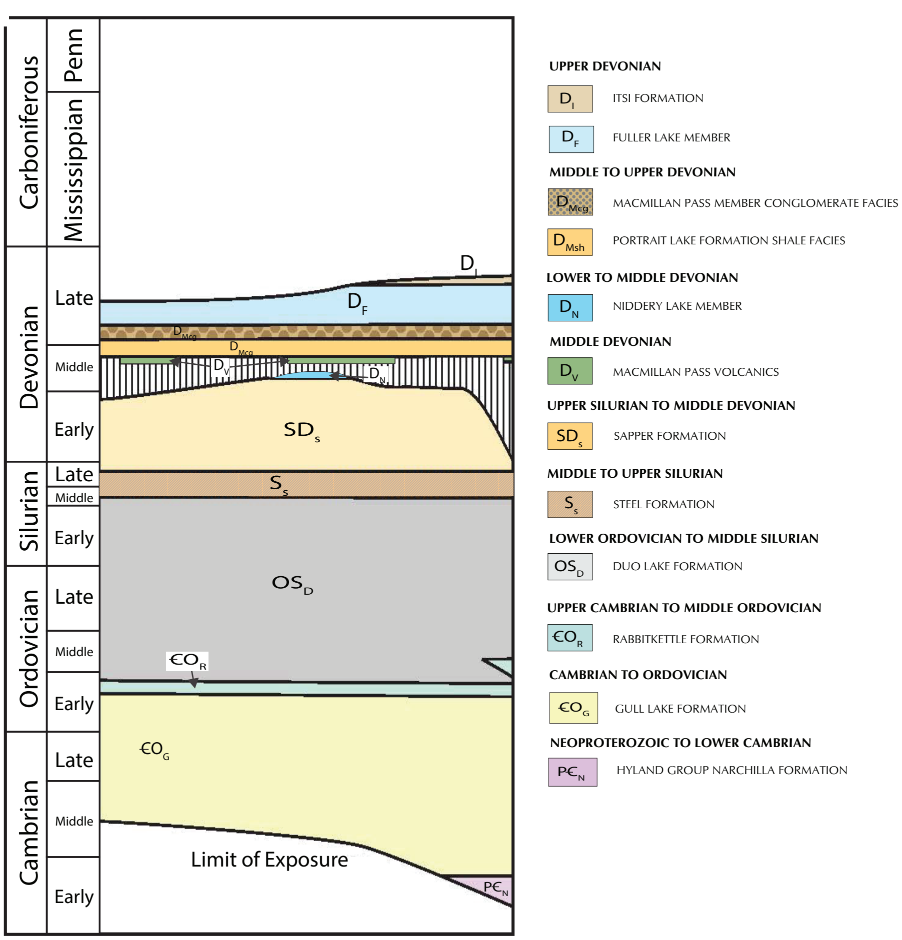

Figure 6. ***(a)*** *Geologic map from the MacMillan Pass district and sample locations; modified from Yukon Geological Survey, 2016.* ***(b)*** *Stratigraphic column of the MacMillan Pass district; modified from Abbott, 2013.*

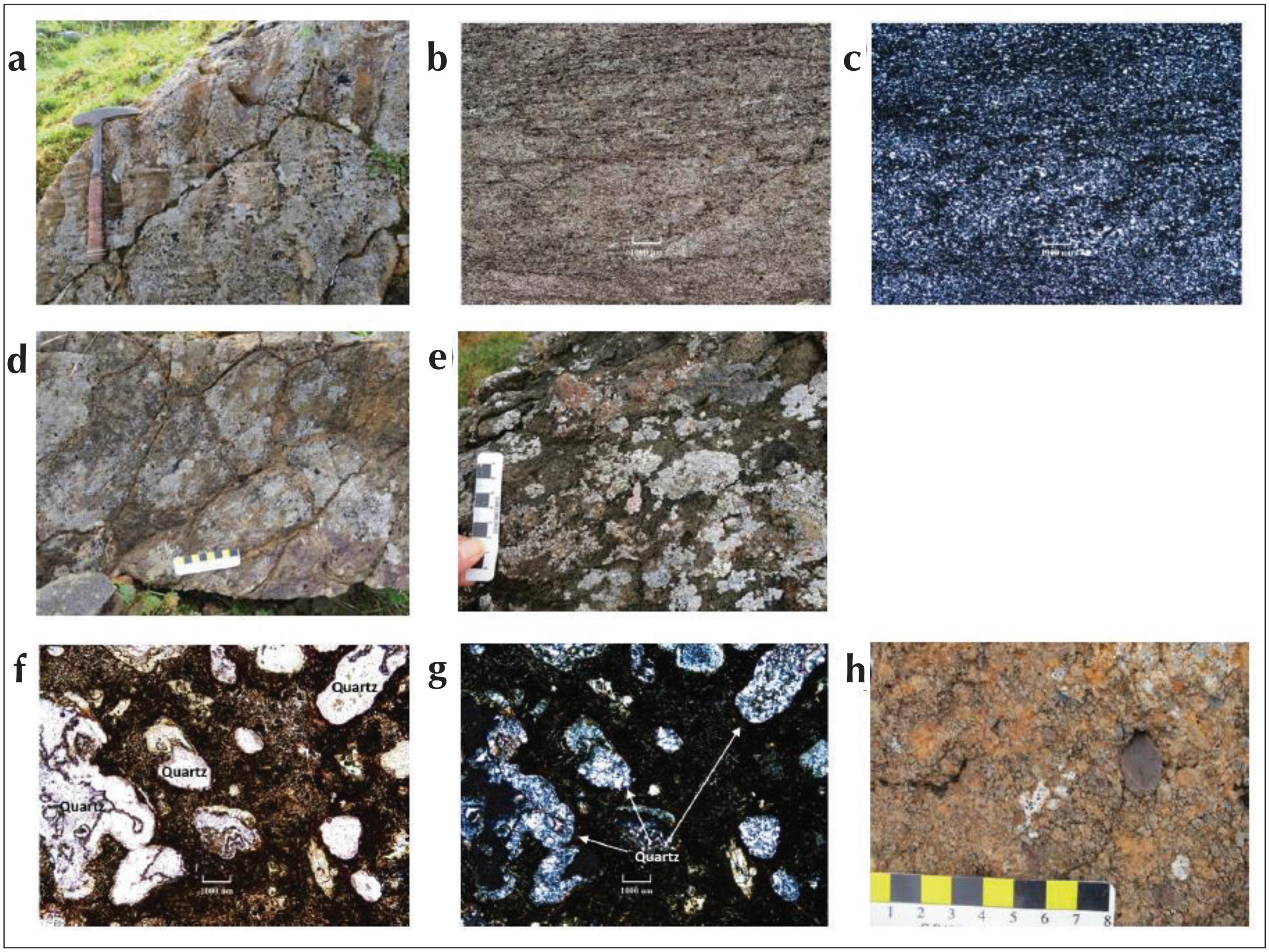

***Figure 7. (a)** Bedded ash and lapilli tuff breccia. Earn Group, Middle Devonian MacMillan Pass volcanic rocks. **(b)** Sample MP-01 is a very fine quartz rich tuff with glass fragments. 5x magnification, plane-polarized light. **(c)** Sample MP-01 in cross-polars. **(d)** Mafic flow with columnar jointing, MacMillan Pass. **(e)** Fragmental flow with scoria, Niddery volcanic rocks. **(f)** Sample MP-45 is a mafic scoria with vesicles filled with quartz. 5x magnification in plane-polarized light. **(g)** Sample MP-45 in cross-polars. **(h)** Heterolithic lapilli tuff breccia comprising pumaceous fragments (whitish), pyroclastic fragments (brown), and chert fragments (black) in a matrix of fine ash. Niddery volcanic rocks.*

Kechika Trough, and possibly the Early Silurian Howard's Pass district. Other Lower Paleozoic volcanic occurrences in other districts that have no known base-metal deposits will also be studied. This will give us a good understanding of the different types of volcanism in the Selwyn basin and will lower the exploration risk inherent in searching for new base-metal deposits. Future work includes using geochronology, and detailed trace element geochemistry to test for temporal and genetic relationships between volcanism and the formation of clastic sediment-hosted Zn-Pb (±Ag, ±Ba) mineral deposits.

Reconnaissance field investigations of volcanic rocks in the Selwyn basin in 2016 defined various styles and types of volcanism associated with base-metal mineralization at different times in the geological history of the basin. The rocks of the Selwyn basin are characterized by a variety of compositions and volcanic processes. Mafic and felsic volcanism occurred intermittently during the lower Cambrian, upper Cambrian-early Silurian, and Late Devonian. The abundance, distribution, and nature of this volcanism are poorly documented and will be further defined with a focus on characterizing any volcanism associated with the genesis of the base-metal deposits.

FUTURE WORK

In the next few years, additional field studies and laboratory analysis of samples collected will be conducted. In 2017, field studies will focus on documenting the stratigraphic and spatial relationships of additional Paleozoic volcanic complexes and deposits within the Selwyn basin. Analytical work will include lithogeochemistry (major, trace, REE), radiogenic isotopes (Nd-Hf), U-Pb geochronology, and petrographic analysis and mineral chemistry using the SEM and electron microprobe. These data will be used to understand the nature of volcanism, primary and secondary (alteration) signatures, basin mineralogy, petrogenesis, and tectonic affinity of the volcanic rocks.

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