Melt inclusions associated with Archean volcanogenic massive sulphide deposits: constraints on the pre-eruptive metal and volatile content of magmas

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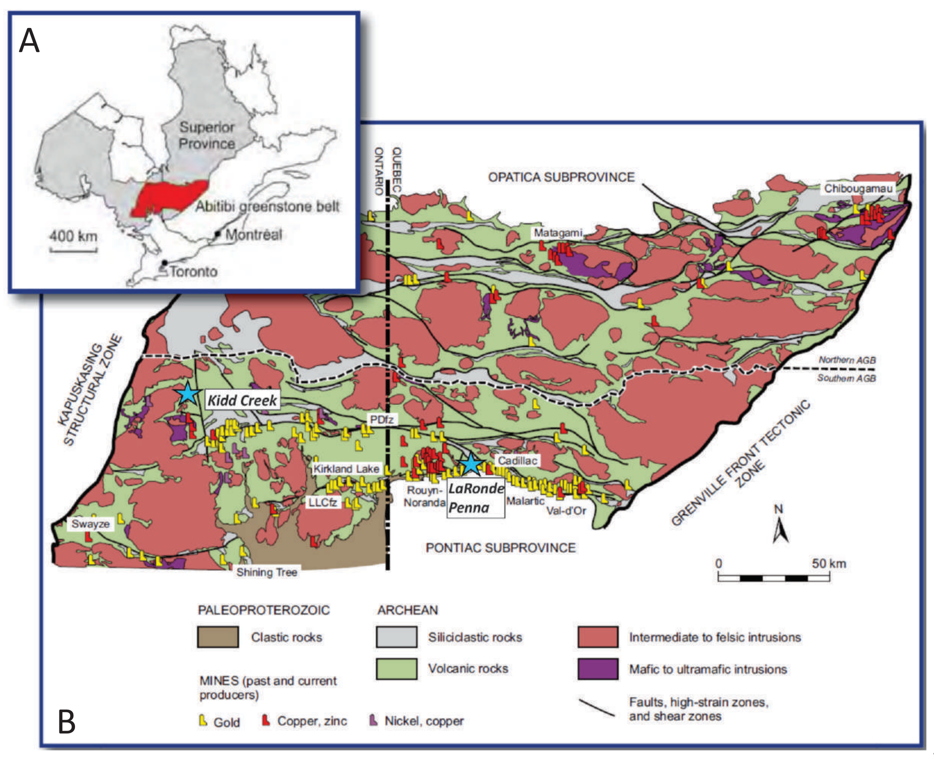
Purpose of study

This first study of melt inclusions (SMI) in Archean volcanogenic massive sulphide (VMS) systems aims to provide insight into their magmatic evolution by characterizing the chemistry of melt inclusions hosted in zircon. Primary melt inclusions in zircon hosted in pre-, syn-, and post- VMS ore-related volcanic units will provide compositional constraints on the initial metal/volatile chemistry of the magma before eruption. This will allow a comparison of the precursor metal budgets of magmas that underwent sulphide saturation, actively degassed, and/or were passively leached, to supply metals to the deposits. Two examples of large VMS deposits, Kidd Creek (KC) and LaRonde Penna (LP), differ greatly in metal tenor and tonnage, in particular in Au endowment (KC - 149 Mt at 0.05 g/t Au; LP - 88 Mt at 5.07 g/t Au; Galley et al., 2007). A significant aspect of this study is to understand why Archean VMS deposits differ so greatly in metal endowment. It may be related to a difference in the primary magmatic metal endowment of coeval volcanics of these deposits, and therefore, the "metal fertility" characteristics of the original source region for the magmas. Studying melt inclusions is a better approach than bulk rock lithogeochemistry to resolving this uncertainty for several of reasons: (i) the trace element concentrations, in particular the metal chemistry, gets significantly modified in bulk volcanic rocks when they are subjected to alteration, mineralization and metamorphism, (ii) melt inclusions provide information about the pre-eruptive/emplacement magmatic metal tenors and volatile contents, and (iii) melt inclusions capture a larger range of magmatic liquid compositions owing to trapping of melts over a prolonged period of host crystal growth, whereas bulk rocks are end-member (final product) compositions of liquid and crystals at the time of eruption/emplacement. In this study, comparisons of magmatic metal endowment in VMS related volcanics in different areas of the Abitibi greenstone belt (ABG) will be made using zircon-hosted SMI to gain perspective on the magmatic liquid compositions associated with different periods of the evolution of the Abitibi subprovince bracketing the KC and LP VMS events. Here, preliminary data for the KC volcanic complex are presented, along with some data from regionally proximal (Tisdale, Kidd Munro, Deloro assemblages) and farfield (Swayze Belt) volcanic assemblages.

Geological setting



The KC VMS deposit is located in the 2720-2710 Ma Kidd Munro assemblage (K-M; Ayer et al. 2002) in western AGB (Fig. 1). At the deposit scale, zircon-hosted melt inclusions are being studied from volcanic rocks stratigraphically divided into three formations (Fig. 2). The main sulphide lenses are hosted in a rhyolitic breccia (Rhyolite formation; Hannington et al., 2017). Melt inclusions from felsic volcanic rocks of the K-M outside of the KC mine complex as well as from the Tisdale ('T'; 2710-2704 Ma; Ayer et al., 2002) and Deloro ('D'; >2725 Ma; Corfu and Noble, 1992) assemblages are also being studied. Additionally, relevant post-Tisdale arc-related intrusive rocks (e.g., Rosseau Pluton; 'RP'; Davis et al., 2000) and a comparable time bracket of volcanic rocks from the Swayze Belt (SB), west of KC (2739-2695 Ma; Van breeman et al., 2006).

Figure 1 - (A) Simplified map of the Superior Province highlighting the Abitibi greenstone belt and (B) Geological map of the Abitibi greenstone belt indicating the main lithological units (Monecke et al., 2017). The KC and LP VMS deposit locations are indicated by the blue stars.

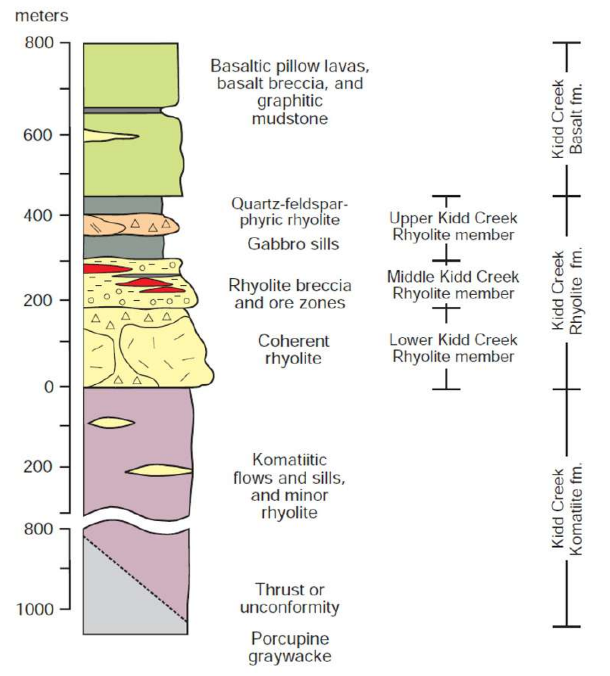


Figure 2 - Stratigraphic column of the KC volcanic complex showing the ore lenses hosted in rhyolitic breccia of the Rhyolite Formation (from Hannington et al., 2017).

Methodologies

Primary methodologies in progress include:

- Thin section petrography to identify lithologies containing zircon and to assess the overall abundance of zircon, and extent of alteration of the volcanic rocks, which impacts the preservation of melt inclusions.
- Melt inclusion petrography to assess the origin, size, depth, shape, preservation, degree of recrystallization, and presence of accidentally trapped phases.
- Scanning electron microscopy (SEM-EDS and -BSE) for semi-quantitative determinations of bulk inclusion composition of exposed melt inclusions.
- Electron microprobe (EPMA) to identify volatile, daughter and accidentally trapped phases.
- Laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) to quantify major and trace element composition of melt and sulphide inclusions buried at depth in zircon, and host zircon chemistry.

Host rock and SMI petrography for Kidd Creek

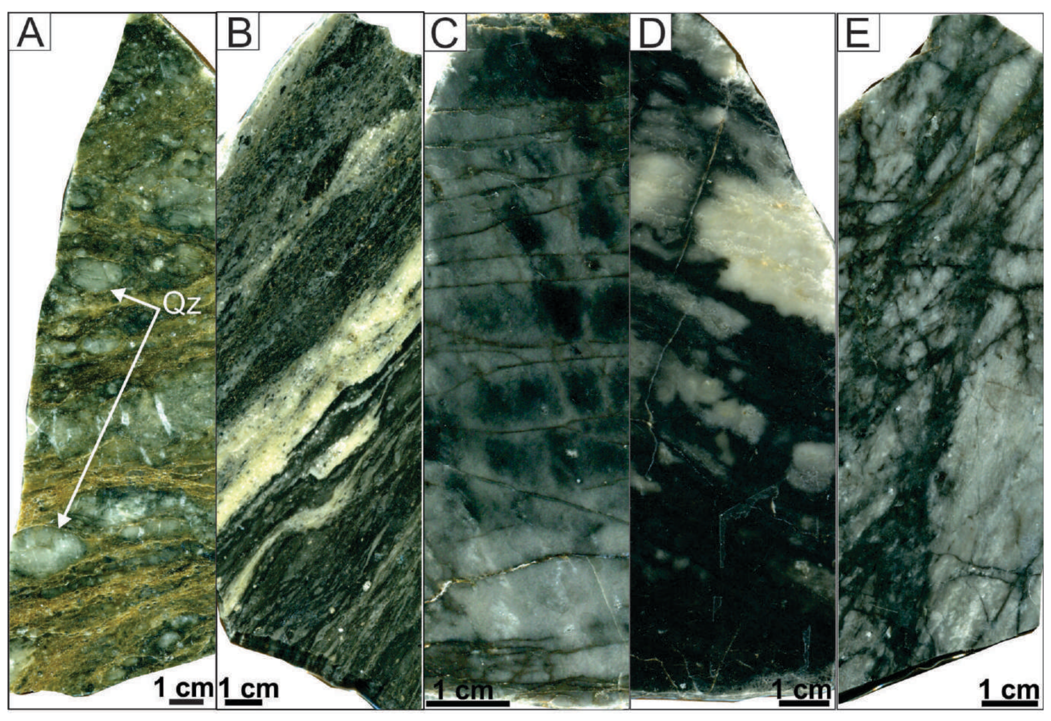


Figure 3 - Representative images of polished hand samples of SMI-bearing lithologies from the KC VMS deposit. (A) Sample 2100-16-20, hanging wall quartz-porphyry; (B) Sample HG-1700-3, hanging wall quartz-porphyry; (C) Sample EO-13, footwall rhyolite; (D) Sample EO-92-5, footwall rhyolite; (E) EO-92-14 footwall rhyolite.

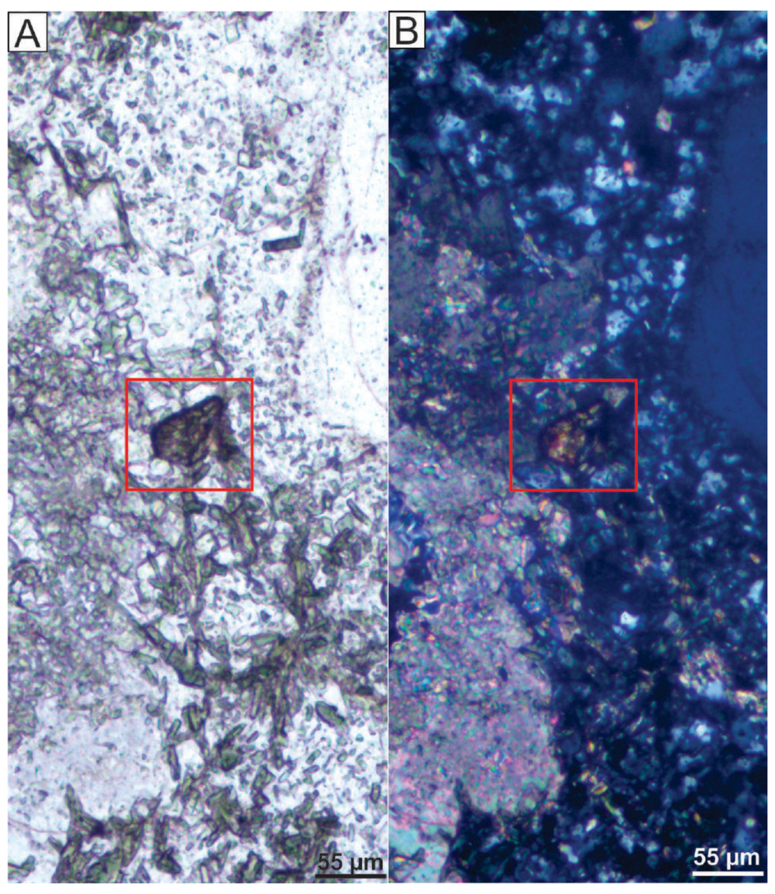


Figure 4 - Photomicrographs showing zircon (highlighted in red boxes) hosted in quartz porphyry actinolite, quartz feldspar, porphyrytic rhyolite from the KC mine in (A) plane-polarized light and (B) crossed-polarized light.

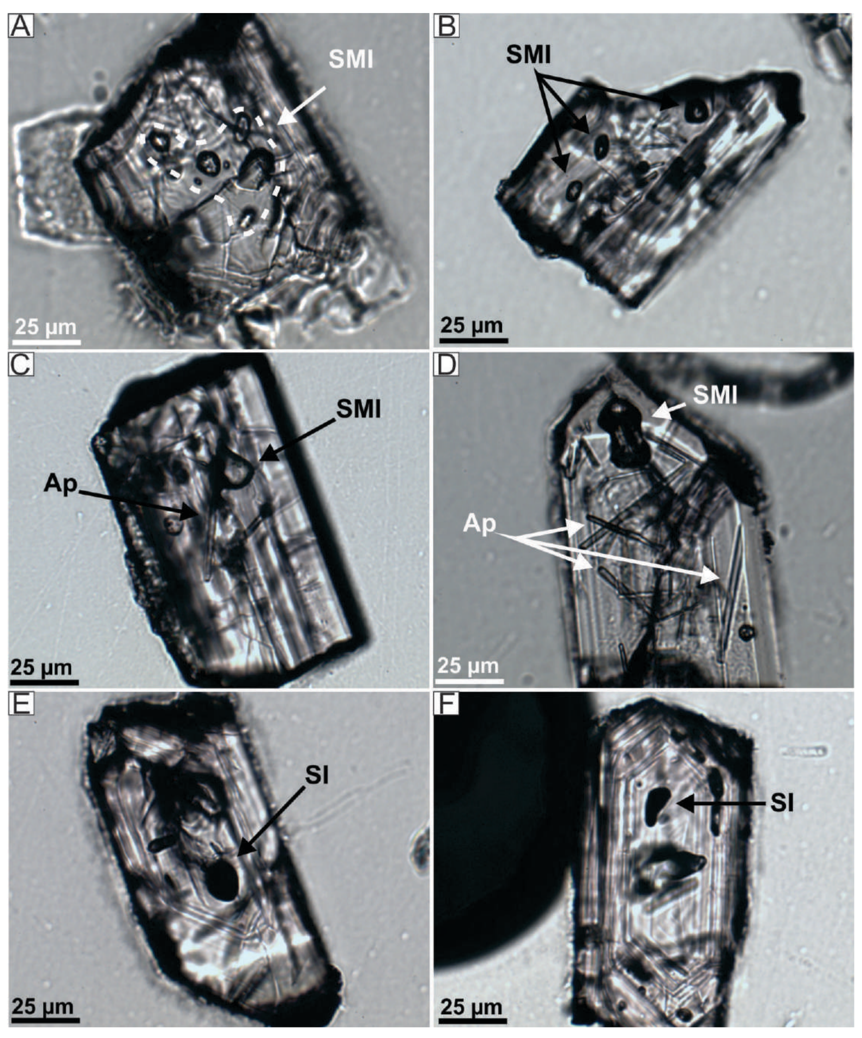


Figure 5 - Photomicrographs (transmitted light) of inclusion-bearing zircons from the KC VMS deposit (sample KC102), containing (A-B) spherical-, and irregular-shaped SMI; (C-D) spherical- to irregular-shaped SMI occurring with needle-like apatite inclusions; (E-F) spherical-shaped, opaque sulphide inclusions. Abbreviations: Ap = apatite; SMI = silicate melt inclusion; SI = sulphide melt inclusion.

Inventory of zircon-hosted inclusion types

Table 1 - Summary of the types (SMI, sulphide, mineral) of inclusions hosted in zircon from various sample lithologies from (A) KC, (B) K-M, (C) T, (D) Upper D, (E) RP and (F-N) SB.

Inclusion type	Sample name						
	A. KC102- hanging wall rhyolite	**B.** 96JAA041- felsic volcanic	**C.** 96JAA087- felsic flow	**D.** C8817- rhyolite	**E.** AG913- biotite-hornblende tonalite	**F.** 93HNB0205b-felsic tuff	**G.** 95HNB0273-massic felsic flow
Silicate melt	x	x	x	x	x	x	x
Sulphide melt							
Quartz	x	x	x	x			x
Biotite		x		x			x
Chlorite	x						
Epidote		x					
Apatite	x	x	x	x	x	x	x
Xenotime	x						
Rutile			x				
Magnetite							
	H. 94HNB0115-feldspar-quartz crystal tuff	**I.** 92HNB0017A2-hornblende tonalite	**J.** 92HNB0123-granodiorite	**K.** 93HNB0087a-felsic lapilli tuff	**L.** 93HNB0206b-quartz-feldspar porphyry	**M.** 94HNB0283-hornblende monzonite	**N.** 92HNB0124-biotite tonalite
Silicate melt	x	x	x	x	x	x	x
Sulphide melt	x						
Quartz					x		
Biotite	x						x
Chlorite							
Epidote						x	
Apatite	x	x	x	x	x	x	x
Xenotime							
Rutile					x		
Magnetite			x			x	

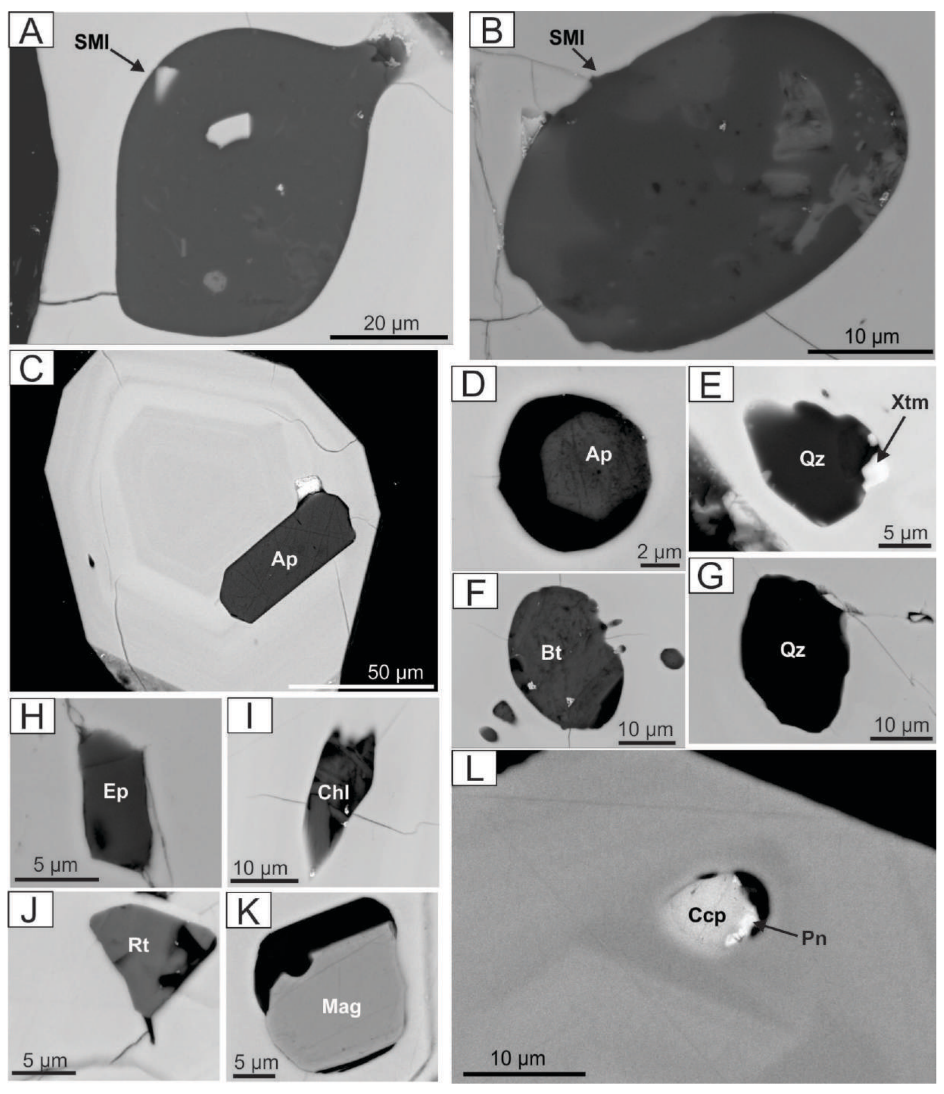


Figure 6 - Scanning electron microscope (SEM-BSE) images of melt, mineral and sulphide inclusions exposed on the surfaces of zircon crystals from various samples studied to date. (A) BSE image showing a blebby, irregular-shaped SMI with a glassy texture; (B) BSE image of a spherical SMI with a microcrystalline texture; (C) BSE image showing a euhedral apatite inclusion occurring in the primary growth zone of zircon; (D) BSE image of prismatic apatite occurring together with a SMI; (E) BSE image of xenotime occurring with quartz; (F-I) BSE images showing euhedral to subrounded silicate mineral inclusions comprising biotite, quartz, epidote, and chlorite; (J-K) BSE images of subangular oxide mineral inclusions containing rutile and magnetite; (L) BSE image showing a spherical, multi-phase sulphide melt inclusion comprising chalcopyrite and pentlandite. Mineral abbreviations: Ap = apatite; Bt = biotite; Chl chlorite; Ccp = chalcopyrite; Ep = epidote; Mag = magnetite; Pn = pentlandite; Rt = rutile; Qz = quartz; Xtm = xenotime.

Bulk SMI composition

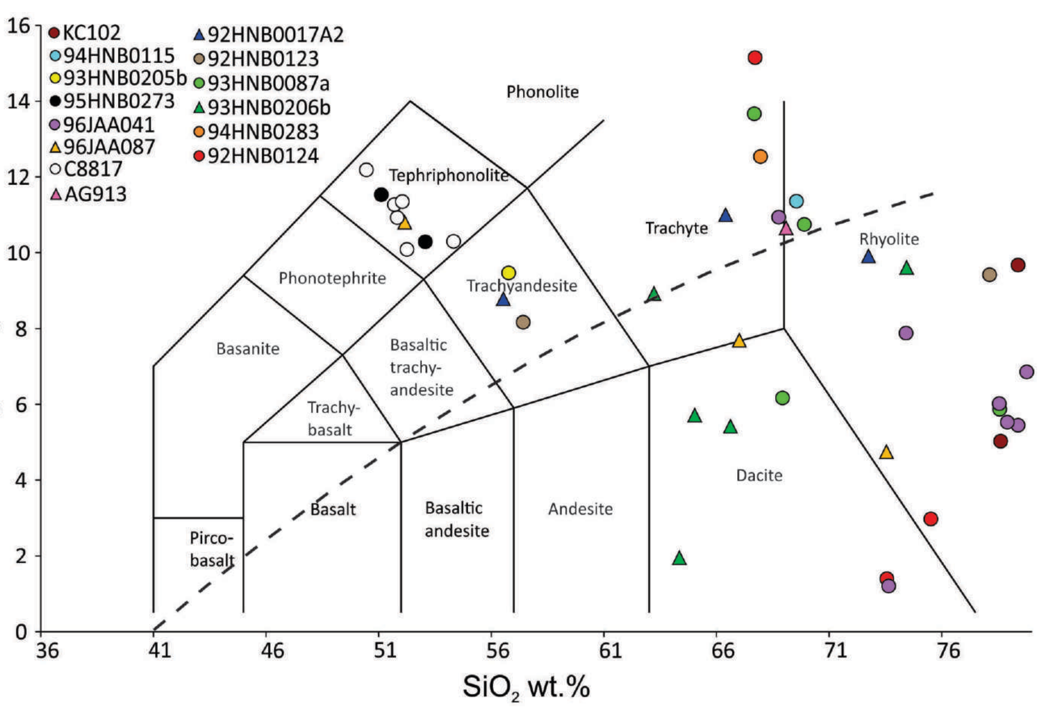


Figure 7 - Total alkalis-silica rock type classification diagram presenting SEM-BSE data on the bulk composition of exposed silicate melt inclusions hosted in zircon from studied volcanic/plutonic lithologies. Note the recognition of alkaline and sub-alkaline SMI compositions as well as variations in SMI composition within single lithologies. See Table 1 for corresponding rock types and sample locations.

Host zircon chemistry

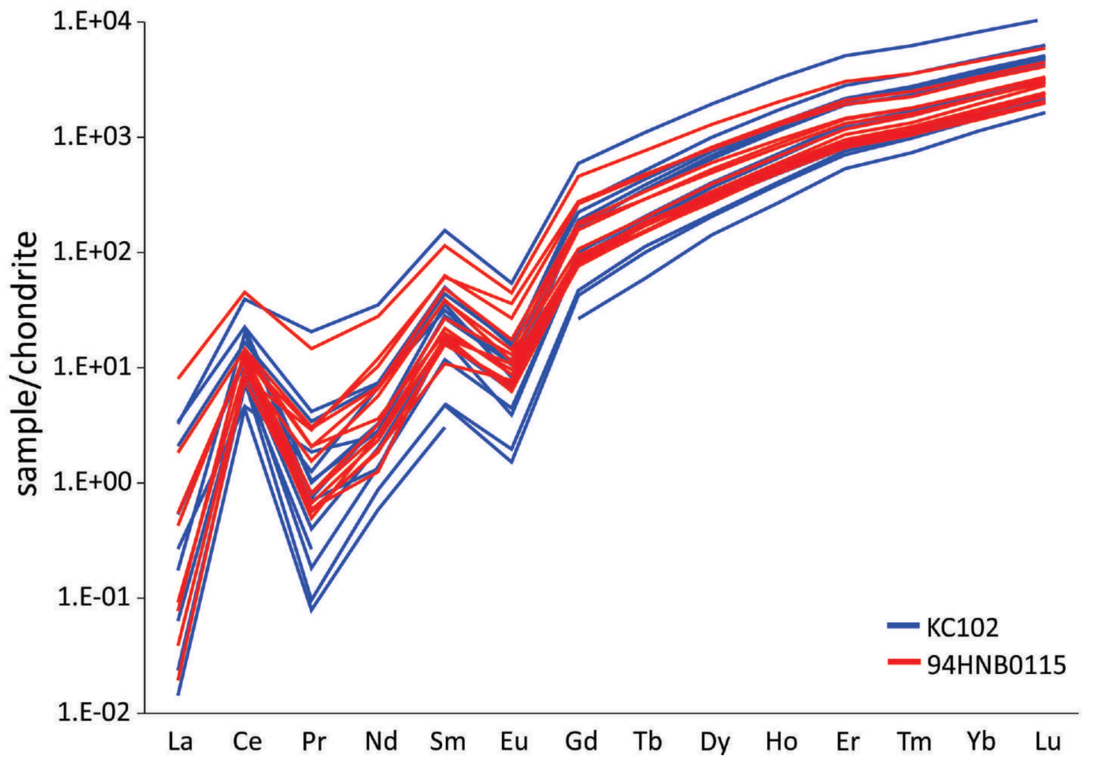


Figure 8 - Chondrite normalized rare earth element diagram showing host zircon chemistry for two samples: Hanging wall rhyolite, KC; feldspar-quartz crystal tuff, SB. Host zircons show characteristic REE patterns of fresh, magmatic zircon.

Summary and future work

- Preliminary data from this study show: (i) a variety of inclusion types (SMI, sulphide melt, mineral) hosted in zircon from KC, localities in close proximity (T, K-M, D) and in distant areas (SB), providing a record of melt composition, oxidation state and degree of sulphide saturation; (ii) the bulk composition of silicate melt inclusions range from high alkaline to high silica, within single lithologies.
- Petrographic and compositional data from the melt inclusions combined with zircon compositional data elucidate links between the magmatic P-T-fO_2 evolution and metal and volatile endowment, providing a means to quantitatively inform mass balance exercises concerning the magmatic contributions to VMS, and differentiate between metal-barren and -fertile volcanic districts. Information gained from this study can possibly be used in making advancements to current genetic models for Archean VMS deposits which can ultimately contribute to exploration criteria for similar deposits.
- Preliminary results from KC will later be compared to results obtained for LP.

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