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RECEIVED 30 April 2024

ACCEPTED 05 June 2024

PUBLISHED 01 July 2024

## CITATION

Carter LC and Williamson BJ (2024), Migration and focusing of porphyry deposit-forming fluids through aplitic mush of the Saginaw Hill cupola, Arizona, United States. *Front. Earth Sci.* 12:1426111. doi: 10.3389/feart.2024.1426111

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# Migration and focusing of porphyry deposit-forming fluids through aplitic mush of the Saginaw Hill cupola, Arizona, United States

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Porphyry-type Cu ± Au ± Mo deposits form in the upper (ca. 2–5 km deep) parts of large, long-lived magmatic-hydrothermal systems in which mineralising fluids are thought to be derived from mid-to shallow-crustal magma chambers. Increasingly, however, magmatic systems are viewed as consisting of mush with minor and transient lenses of magma, with mush being a variably packed framework of crystals with interstitial melt and magmatic volatile phase (MVP). In this context, questions remain as to the source (mainly depth) and mechanisms of transport and focussing of the vast volumes of fluids required for shallow level porphyry-type mineralisation. Even more problematic is a paucity of first-order textural evidence for the presence of mush in magmatic-hydrothermal systems, including those which host porphyry-type deposits. To address this, we have studied the aplitic porphyry cupola of the Saginaw Hill magmatic system, Tuscon, Arizona, United States, where magmatic-hydrothermal features are exceptionally well exposed, including a massive silica cap, quartz unidirectional solidification textures (USTs), stockworks of multiple generations of variably mineralised quartz veins and mineralised miarolitic cavities. From field-to micro-scale textural and geochemical studies, particularly observations of vermiform quartz between earlier generations of magmatic quartz and feldspar, we evidence the development of fluid pathways through mush at the magmatic-hydrothermal transition. These are shown to connect and provide fluids and ore constituents to the mineralised miarolitic cavities and early quartz vein stockworks. We suggest that this process should be considered in all new genetic, exploration and numerical models for porphyry and similar types of magmatic-hydrothermal ore-deposits.

## KEYWORDS

porphyry, copper, mush, miarolitic cavities, magmatic-hydrothermal, fluid exsolution

## 1 Introduction

Porphyry deposit-forming fluids are derived from large, long-lived magmatic-hydrothermal systems in subduction- and collision-related tectonic setting (e.g., Richards, 2005; Seedorff et al., 2005; Sillitoe, 2010). Less well understood are the mechanisms by which sufficient volumes of mineralising fluids are

extracted and focused into narrow, shallow (ca. 2–5 km) zones of porphyry-style mineralisation.

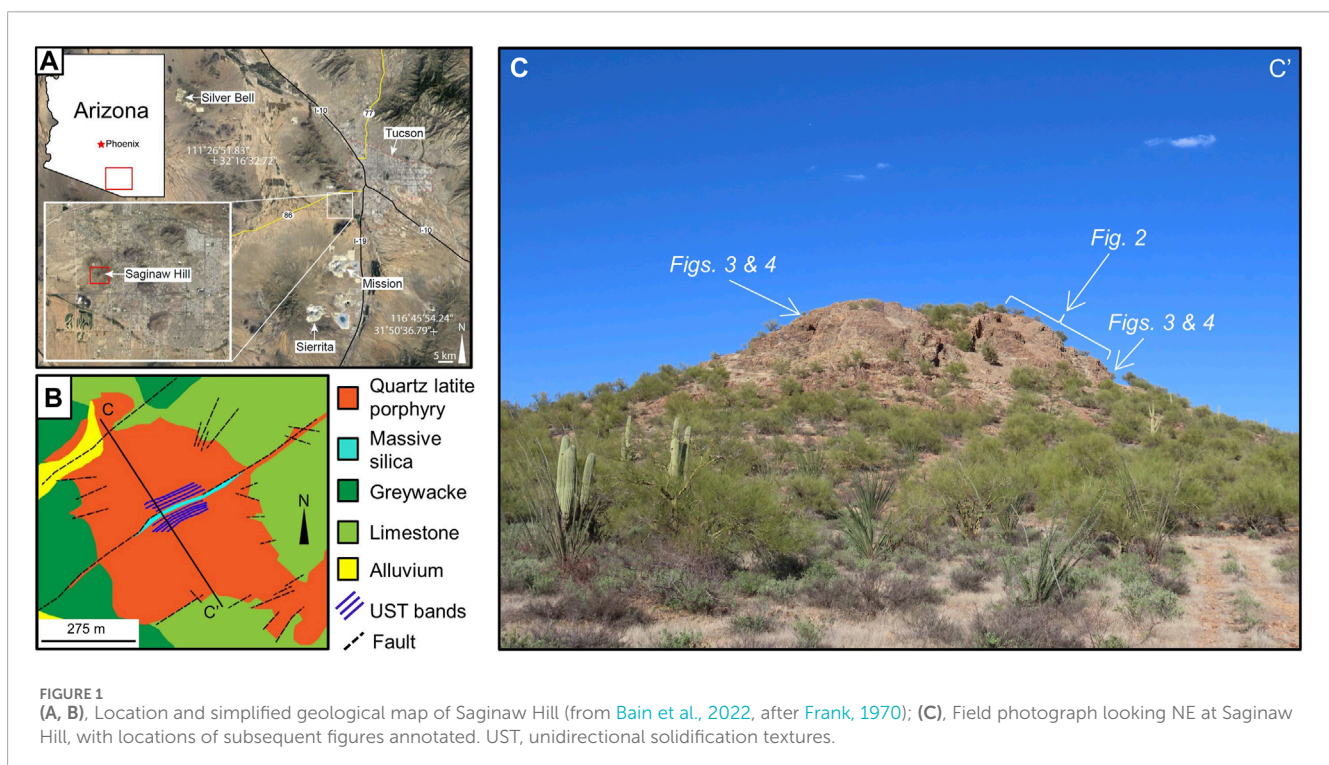
Traditional models for porphyry deposit formation invoke direct release of mineralising fluids from magmas in stocks, cupolas, and/or dykes in the upper parts of magma chambers (e.g., Dilles, 1987; Cloos, 2001; Richards, 2005; Sillitoe, 2010). However, it is difficult to envisage how the vast volumes of fluids required to form porphyry deposits and their associated alteration could be supplied from such volumetrically small magmatic bodies (Seedorff et al., 2005; Sillitoe, 2010). It has been suggested that fluids could be derived from a larger underlying magma chamber (e.g., Dilles, 1987; Large et al., 2021), but how they migrate and are focussed into the zone of porphyry mineralisation is often overlooked or vague. In addition to this, the classic concept of large melt-dominated magma chambers in the upper crust is being increasingly questioned. From thermal and physical modelling they are unlikely to form or to endure for long enough to generate their varied compositions and textures (Cashman et al., 2017). There is also little evidence from geophysical imaging for large volumes of melt-dominated magma in the upper crust, even below currently active volcanoes (Cashman et al., 2017; Sparks and Cashman, 2017; Jackson et al., 2018).

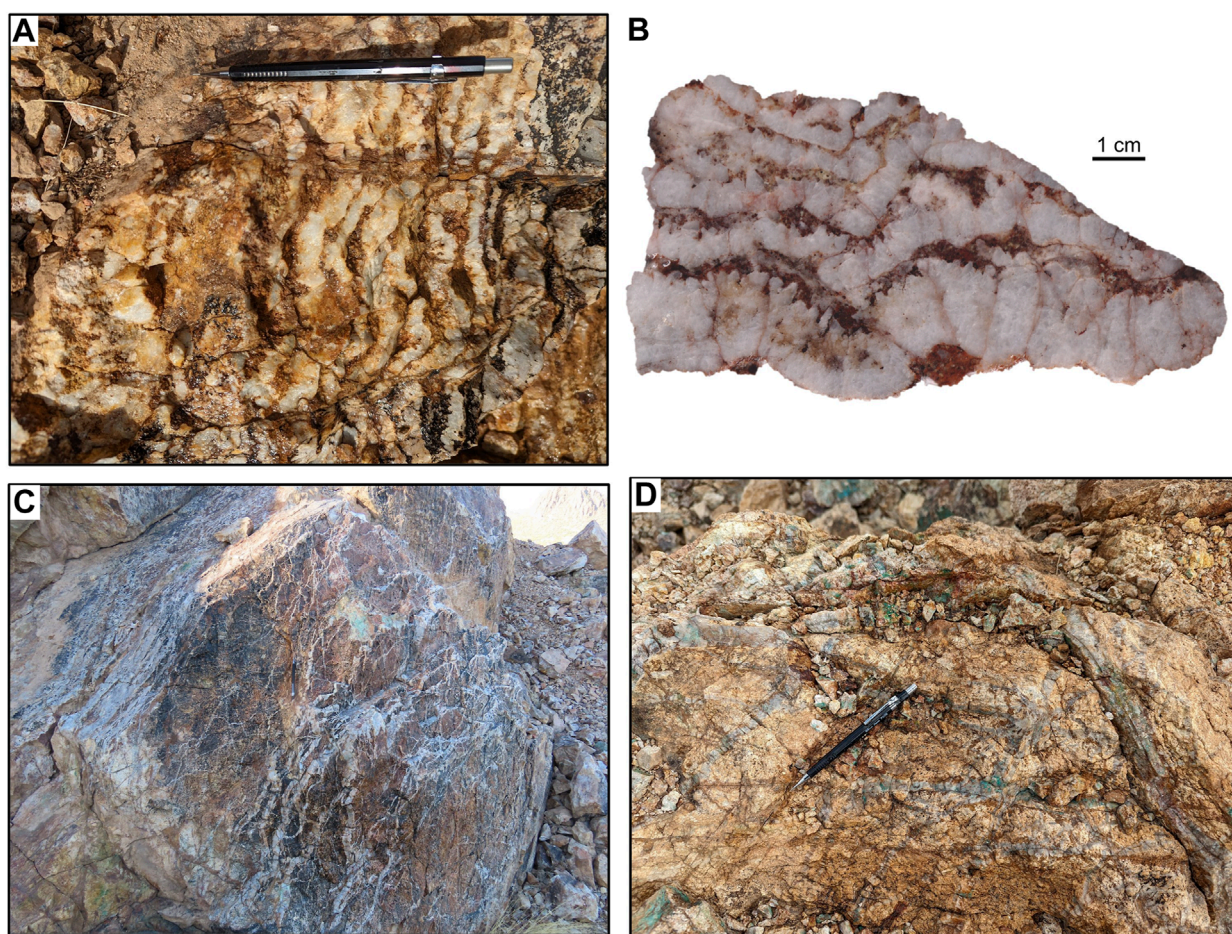
Increasingly, melt reservoirs are viewed as transcrustal magmatic systems which consist of occasional and transient lenses of magma within what is termed mush, a semi-rigid 3D framework of crystals with interspersed melt and magmatic volatile phase (MVP) (e.g., Cashman et al., 2017). The transition from magma to mush is thought to occur when crystal concentrations reach between 50% and 65% (Cashman et al., 2017; Sparks and Cashman, 2017). The ability of fluids to flow through a semi-crystalline mush is rapidly gaining acceptance (e.g., Cashman et al., 2017; Holness, 2018; Carter et al., 2021; Blundy, 2022). Evidence of this occurring

in lower crustal hot zones is from the presence of networks of interstitial sulphides in amphibole-olivine-pyroxene cumulates (Holwell et al., 2022) and experimental studies demonstrating percolative reactive melt flow (Blundy, 2022). Textural evidence for these processes occurring in the shallow crust is, however, still relatively rare, probably due to a lack of vertically extensive exposures (Seedorff et al., 2008) and perhaps because of a reluctance to accept the relatively radical concept of transcrustal mush systems. It has only been reported from the root-zone of one porphyry system (Ann Mason in the Yerington District, Nevada), where Carter et al. (2021) showed interconnected networks of multiple quartz generations joined to mineralised miarolitic cavities within the groundmass of aplitic porphyry dykes. However, without more textural and complementary experimental evidence, the concept of mush in the shallow crust will continue to be questioned, including its importance in the generation of porphyry-type deposits. To further address this, we study the granitic cupola at Saginaw Hill, Tucson, Arizona, United States (Frank, 1970), where magmatic-hydrothermal features are exceptionally exposed including a massive silica cap, quartz unidirectional solidification textures (USTs), stockworks of multiple generations of variably mineralised quartz veins and mineralised miarolitic cavities. We integrate field to micro-scale textural and geochemical observations to evidence magmatic-hydrothermal fluid flow within mush and its link to mineralisation.

## 2 Geological setting

The Saginaw Hill system, located 15 km southwest of Tucson, Arizona, is a composite pluton mainly comprised of quartz latite porphyry and quartz monzonite porphyry (Figure 1). It has a total





**FIGURE 2** (A, B) Field photograph and polished slab of the quartz-aplite unidirectional solidification texture (UST) layers; (C), Field photograph showing the UST layers (top left) transitioning into anastomosing quartz veins (bottom right). Pencil in middle of photograph for scale; (D), Field photograph, a few metres downhill from (C), of quartz stockwork veining in the Saginaw Hill quartz latite porphyry. Some veins are seen hosting secondary Cu mineralisation, which probably is the result of *in-situ* oxidation of primary sulphides.

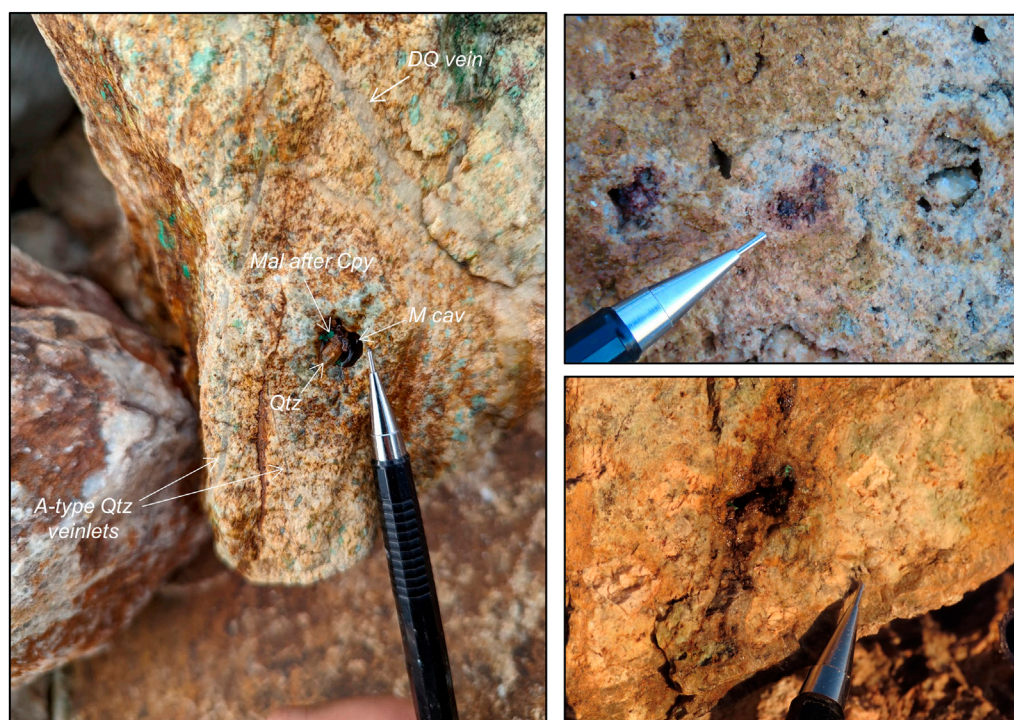
surface outcrop of approximately  $\sim 0.3 \text{ km}^2$ , and has intrusive (chilled) and faulted contacts with limestone and greywacke units of the Cretaceous Amole Group (Frank, 1970; Bain et al., 2022). Recent zircon U-Pb dating of porphyry rocks and dykes from Saginaw Hill yielded an age of  $60.0 \pm 0.6 \text{ Ma}$  (Greig, 2021), similar to that of the Sierrita-Esperanza ( $\sim 55 \text{ Ma}$ ), Mission Pima ( $\sim 58 \text{ Ma}$ ), and Silver Bell ( $\sim 68 \text{ Ma}$ ) porphyry systems (Singer et al., 2008), which were situated close to Saginaw Hill prior to Tertiary tilting and extension (Stavast et al., 2008).

Exposed on Saginaw Hill is a sericitically altered aplitic porphyry cupola zone of the system which hosts significant magmatic-hydrothermal features. This includes a several meter thick zone of massive homogeneous quartz which runs along the sub-vertical northeast-striking Papago Queen fault (Frank, 1970). Bain et al. (2022) describe this as a massive quartz vein, however it cannot be traced along strike away from Saginaw Hill and historic drill holes did not intercept it at depth (Frank, 1970), so it is more likely a massive silica body or cap (see Kirwin, 2005; Carter and Williamson, 2022) that has been tilted and juxtaposed against the Papago Queen fault. The massive silica cap transitions southward

into a  $\sim 10 \text{ m}$  zone of spectacular sub-vertical/sub-parallel rhythmically layered quartz-aplite unidirectional solidification textures (USTs), with quartz comprising from 75% to 95% of the rock volume (Frank, 1970; Bain et al., 2022; Figure 2). The UST zone grades further out for  $\sim 30 \text{ m}$  into locally intense stockworks of anastomosing and sheeted Cu-mineralised quartz veins as well as Cu-mineralised miarolitic cavities within the quartz latite porphyry (Figure 3), with quartz veins comprising up to  $\sim 45\%$  to the rock volume (Frank, 1970).

### 3 Methods

Field observations and samples of mineralised miarolitic cavities were taken from Saginaw Hill, a few metres outward from the UST layers, between the mineralised quartz veins. A subset of samples were prepared as  $30 \mu\text{m}$ -thick polished thin sections for optical microscopy, QEMSCAN<sup>®</sup> automated mineralogy, and SEM-EDS-CL imaging and EPMA analysis at Camborne School of Mines, University of Exeter, United Kingdom. The SEM-CL images



**FIGURE 3**

Field photographs of mineralised miarolitic cavities (undoubted textural evidence for fluid exsolution; Candela, 1997) in the Saginaw Hill quartz latite porphyry. All examples are a few metres outward from the UST zone at the crest of Saginaw Hill. The miarolitic cavities are seen closely associated with early DQ and A-type quartz veins (nomenclature after Gustafson and Hunt, 1975; Cernuschi et al., 2023). M Cav, miarolitic cavity; Qtz, quartz; Mal, malachite; Cpy, chalcopyrite.

presented have been false coloured on a linear look-up table to allow for better visualisation of the quartz generations. EPMA was used to measure Ti concentrations in quartz. The lower limit of detection for Ti was 24 ppm, calculated as  $3\sigma$  above the average background counts, and analytical uncertainty was  $\pm 14$  ppm, estimated from the repeat analysis of a quartz reference material provided by A. Audétat (Audétat et al., 2014). Quartz crystallisation temperatures were calculated using the TitaniQ geothermometer of Wark and Watson (2006), using an  $a_{\text{TiO}_2}$  of one given the presence of rutile in the assemblage. Full methods are described in Supplementary Material S1. QEMSCAN<sup>®</sup>, SEM-CL and EPMA data are presented in Supplementary Material S2–S4.

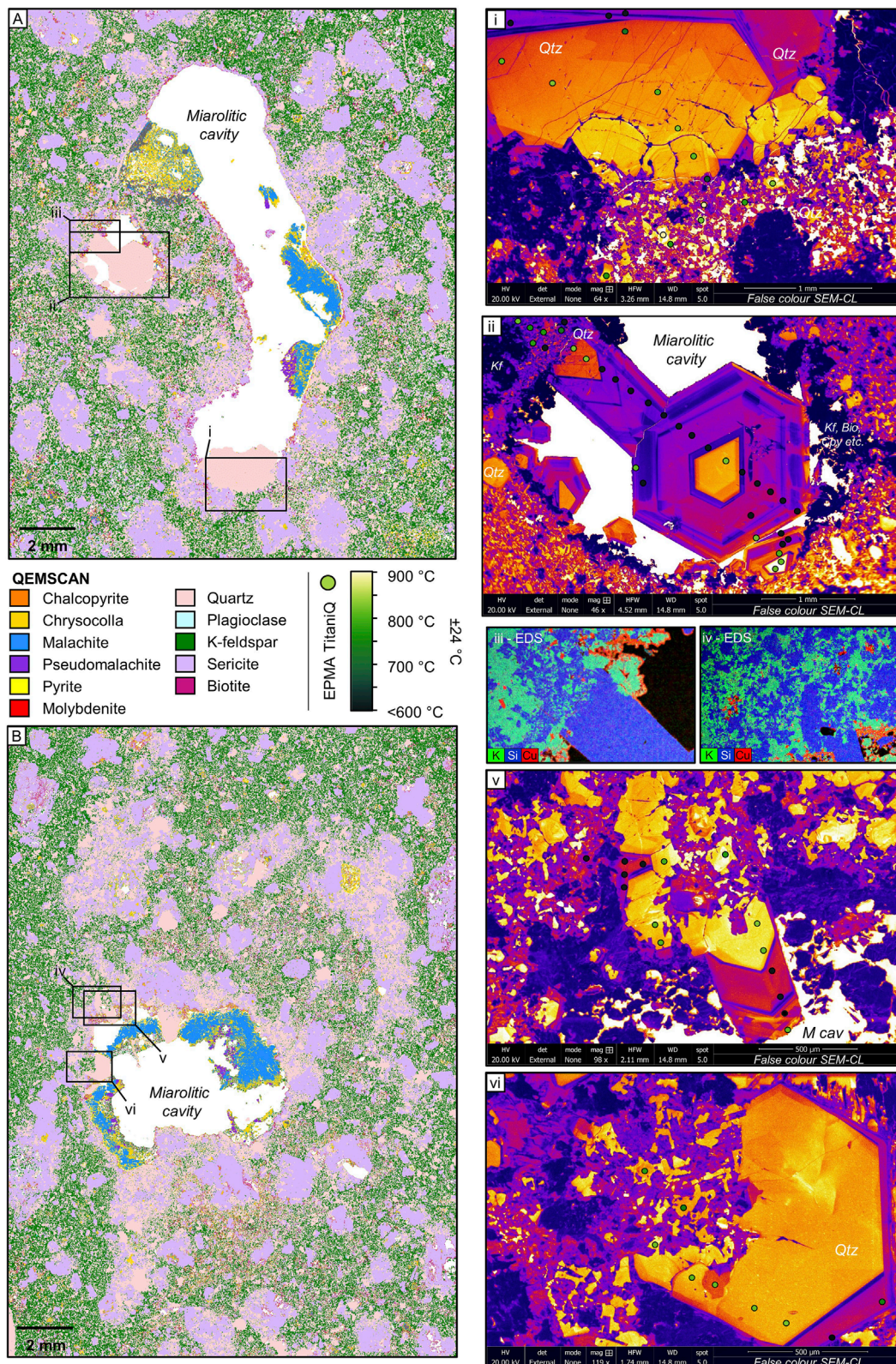
#### 4 Field-to micro-scale observations of quartz veinlets and related mineralisation

Miarolitic cavities are undoubted textural evidence of magmatic-hydrothermal fluid exsolution (Candela, 1997). Numerous quartz-lined miarolitic cavities can be found in the quartz latite porphyry on the slopes of Saginaw Hill, outward from the UST bands and are closely associated with stockworks of multiple quartz vein generations, including likely deep quartz (DQ) veins (continuous, sugary to massive; see Cernuschi et al., 2023) as well as sinuous, sugary, A-type quartz veinlets (nomenclature of Gustafson and Hunt, 1975) (Figure 3). The cavities range from <1 to several cm across, and some are mineralised with secondary malachite,

pseudomalachite and chrysocolla, which likely formed *in situ* from the oxidation of primary chalcopyrite. They are locally abundant, with several dozen per m<sup>2</sup> of outcrop.

From QEMSCAN<sup>®</sup> mineralogical maps and SEM-EDS-CL imaging, the rhyolitic groundmass hosting the cavities is comprised of K-feldspar and polycrystalline, branching, highly interconnected multiple generations of vermiform quartz (moderate to dark CL response), in addition to discrete magmatic quartz grains (brighter CL response) (Figure 4). Phenocrysts of magmatic quartz are also present along with relict phenocrysts of plagioclase and/or K-feldspar that appear to have been entirely replaced by secondary sericite. This alteration appears particularly prevalent around cavities and in certain channels of the aplitic groundmass, and does not appear to be fracture controlled. This may be an expression of coarse muscovite-type alteration (see Runyon et al., 2019), which is being increasingly recognised as a late, relatively low-temperature overprint in the exposed root zones of porphyry systems in Arizona and Nevada.

From SEM-EDS-CL images (Figure 4), the cavities contain well defined, zoned, multiple generations of inwardly grown bright, moderate and dark CL quartz. From TitaniQ temperature estimates, the bright CL quartz crystallised at  $\sim 700^\circ\text{C}$ – $840^\circ\text{C}$  ( $\sim 80$ – $200$  ppm Ti), moderate CL quartz  $< 600^\circ\text{C}$ – $700^\circ\text{C}$  ( $\sim 24$ – $80$  ppm Ti) and the dark CL quartz  $< \sim 600^\circ\text{C}$  ( $< 24$  ppm Ti). Our temperature estimate for the dark CL quartz is an approximate maximum as constrained from the EPMA lower detection limit for Ti, hence the dark CL quartz could have crystallised at any temperature below  $600^\circ\text{C}$ . The relationship between quartz CL response and TitaniQ temperature aligns with previous studies (e.g., Müller et al., 2010; Carter and



Williamson, 2022; Müller et al., 2023), including that of Carter et al. (2021) which used Total-IBA to ground-truth CL responses against Ti concentrations in quartz in mineralised miarolitic cavities.

The vermiform quartz in the aplitic groundmass has the same CL response as the quartz in the miarolitic cavities. Further, the moderate to dark CL quartz appears to form continuous, interconnected networks between the earlier bright CL quartz. The bright CL quartz in the aplitic groundmass has notably irregular, jagged, edges, indicating that it was either brecciated or, where in contact with the dark CL quartz, partially resorbed (Figures 4A–D). The interconnected quartz networks can be traced continuously to the edges of the prepared thin sections. Their high degree of connectivity in 2D must mean even higher orders of connectivity in 3D. Cu-bearing oxide and carbonate phases (likely secondary after primary chalcopyrite) can be found as inclusions in all of the quartz generations, but within the miarolitic cavities, mineralisation appears to post-date the earliest, brightest CL quartz generation.

## 5 Textural development and mineralisation in the Saginaw Hill cupola

At Saginaw Hill, we interpret the massive silica body and USTs to have formed as a result of undercooling which occurred during emplacement of magma into the cupola of the pluton and rapid pressure fluctuations due to rhythmical “first-type boiling.” Their close association with abundant continuous, sugary to massive DQ quartz veins (nomenclature after Cernuschi et al., 2023) and A-type (sugary, sinuous and intermittent) quartz veinlets (nomenclature after Gustafson and Hunt, 1975) suggests that they were produced close to the magmatic-hydrothermal transition. This model follows those previously suggested for similar textures in porphyry deposit-forming magmatic-hydrothermal systems elsewhere (e.g., Kirwin, 2005; Carter and Williamson, 2022; Müller et al., 2023).

The aplitic groundmass of the Saginaw Hill cupola shows direct evidence for the exsolution of mineralising fluids and the magmatic-hydrothermal transition, mainly the presence of mineralised miarolitic cavities closely associated with DQ and A-type quartz veins (Figures 3, 4). From our micro-textural and geochemical observations, the aplitic groundmass contains multiple generations of paragenetically late interconnected vermiform quartz which directly link to mineralised miarolitic cavities (Figure 4). We interpret these as recording the pathways of mineralising fluids which flowed through spaces between earlier formed quartz, feldspar and accessory phases in a mush; i.e., palaeo-permeability which allowed ore-forming fluids to ascend from larger volumes of underlying magmas. Such a mechanism has been previously suggested for the formation of vermiform quartz and mineralised miarolitic cavities in aplitic dykes of the Yerington district, Nevada (Carter et al., 2021). Both potassic and sericitic alteration in the Saginaw Hill cupola also appear to have occurred due to such fluid flow since there are no obvious fracture pathways in the aplitic groundmass. From these observations, the mineralisation and potassic and sericitic alteration associated with the vermiform quartz can be interpreted as intra-mush auto-metasomatic.

Interconnected miarolitic cavities have been recognised in granitic porphyry intrusions hosting the Baja de la Alumbrera porphyry Cu-Au deposit, Argentina (Harris et al., 2004), and other granitic systems (Candela and Blevin, 1995), however not in the context of a magmatic-hydrothermal mush system. That mush microstructures were not recognised in these studies is probably because the necessary micro-scale imaging and analysis was not applied, and due to a paucity of previous direct physical evidence and models for the occurrence of mush in magmatic systems (see Introduction). Our new observations from Saginaw Hill suggest that fluid flow through mush, and associated mineralisation, may occur in the aplitic cupolas of plutons in porphyry-forming magmatic-hydrothermal systems. This builds on the suggestion of such processes occurring, on a much smaller scale, in aplitic dykes which feed porphyry mineralisation in the Yerington district, as evidenced by Carter et al. (2021).

The key implication of our observations of the aplitic mush microtexture is that fluids can be decoupled from silicate melts and crystals and travel upwards until they precipitate ore and gangue minerals, almost certainly by the process of percolative reactive flow (Blundy, 2022). This would allow a much larger volume of fluids to be involved in mineralisation, sourced from much more extensive portions of the underlying (sub-cupola) mush system, and over much longer time periods than previously assumed.

Prolonged fluid flow through an episodically open mush system aligns with recent geochronological studies of porphyry deposit formation which suggest that magmatic-hydrothermal mineralisation was much longer lived and generally relatively late compared with the shallow magmatic parts of the system, occurring over periods in excess of 1.5 Myrs after emplacement of host magmatic rocks (e.g., Romero Kojima et al., 2010; Stein, 2014; Spencer et al., 2015; Chang et al., 2017; Chiaradia and Caricchi, 2017; Li et al., 2017; Carter et al., 2022). This longevity can be explained by ongoing mush processes focussing fluids from deeper, longer-lived portions of a multi-intrusive and probably stepwise evolving mush system.

The suggested mechanisms and timescales by which mineralising fluids migrate and are focussed into the relatively narrow and shallow zones of porphyry-style mineralisation should be incorporated into future porphyry formation and exploration models. They also highlight the need to re-address the temporal-thermal frameworks that form the basis of numerical simulations of porphyry and similar magmatic-hydrothermal systems.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

## Author contributions

LC: Conceptualization, Formal Analysis, Investigation, Methodology, Writing—original draft, Writing—review and editing. BW: Conceptualization, Writing—review and editing.

## Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. LC was supported by LC Geoscience Ltd. BW received funding from NERC Highlight Topic award “From arc magmas to ores (FAMOS): A mineral systems approach” [NE/P017452/1].

## Acknowledgments

This research was allied to the NERC Highlight Topic award “From arc magmas to ores (FAMOS): A mineral systems approach” [NE/P017452/1], and members of the consortium are thanked for the fruitful discussions. M. Pfau, D. Laux, M. Poodts and I. Simon are thanked for field support. G. K. Rollinson, J. C. Andersen and S. Broom-Fendley (Camborne School Mines, University of Exeter) are thanked for QEMSCAN<sup>®</sup> analysis and EPMA support respectively. A. Audétat is thanked for the piece of quartz reference material for EPMA analysis. F. Cernuschi and Axel Müller are thanked for their constructive comments.

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## Conflict of interest

Author LC is a director of LC Geoscience Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2024.1426111/full#supplementary-material>

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