



Magmatic controls on the genesis of porphyry Cu–Mo–Au deposits: The Bingham Canyon example



Carter Grondahl, Zoltán Zajacz*

University of Toronto, 22 Russell Street, Toronto, M5S 3B1, Canada

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ABSTRACT

Bingham Canyon is one of the world's largest porphyry Cu–Mo–Au deposits and was previously used as an example to emphasize the role of magma mixing and magmatic sulphide saturation in the enhancement of ore fertility of magmatic systems. We analyzed whole rocks, minerals, and silicate melt inclusions (SMI) from the co-genetic, ore-contemporaneous volcanic package (~38 Ma). As opposed to previous propositions, whole-rock trace element signatures preclude shoshonite–latite genesis via mixing of melanephelinite and trachyte or rhyolite, whereas core to rim compositional profiles of large clinopyroxene phenocrysts suggests the amalgamation of the ore-related magma reservoir by episodic recharge of shoshonitic to latitic magmas with various degrees of differentiation. Major and trace element and Sr and Nd isotopic signatures indicate that the ore-related shoshonite–latite series were generated by low-degree partial melting of an ancient metasomatized mantle source yielding volatile and ore metal rich magmas. Latite and SMI compositions can be reproduced by MELTS modeling assuming 2-step lower and upper crustal fractionation of a primary shoshonite with minimal country rock assimilation. High oxygen fugacities (\approx NNO + 1) are prevalent as evidenced by olivine–spinel oxybarometry, high SO₃ in apatite, and anhydrite saturation. The magma could therefore carry significantly more S than would have been possible at more reducing conditions, and the extent of ore metal sequestration by magmatic sulphide saturation was minimal. The SMI data show that the latites were Cu rich, with Cu concentrations in the silicate melt reaching up to 300–400 ppm at about 60 wt% SiO₂. The Au and Ag concentrations are also high (1.5–4 and 50–200 ppb, respectively), but show less variation with SiO₂. A sudden drop in Cu and S concentrations in the silicate melt at around 65 wt% SiO₂ in the presence of high Cl, Mo, Ag, and Au shows that the onset of effective metal extraction by fluid exsolution occurred at a relatively late stage of magma evolution. Overall, our results show that fluid exsolution during simple magmatic differentiation of oxidized alkaline magmas is capable of producing giant porphyry Cu deposits.

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1. Introduction

Porphyry-type ore deposits supply most of the world's Cu, Mo, and Re, and a significant amount of Au, Ag, Sn, and Pd. These deposits generally form at destructive plate boundaries and derive their metal and S budget from magmas degassing at depth (e.g., Cline and Bodnar, 1991; Landtwing et al., 2010; Richards, 2011). The processes necessary to create ore metal- and S-rich fluids by magma degassing at depth are still debated. Some studies suggest that these fluids may be generated by simple magmatic fractionation and crystallization-driven degassing (e.g. Cline and Bodnar, 1991). Others invoke the late-stage introduction and possible mix-

ing of mafic magma into an otherwise felsic magma chamber, with an accompanied flux of S and ore metals (Hattori and Keith, 2001; Halter et al., 2005).

A key parameter concerning porphyry deposit genesis is oxygen fugacity (f_{O_2}), because it has a great impact on the geochemical behavior of S and S-complexed ore metals. At subvolcanic depth, S partitions into the magmatic volatile phase (MVP) more strongly in its reduced form (S²⁻; Zajacz et al., 2012a), and ligands with S in low oxidation state (HS⁻, S₃⁻) are more effective for ore metal complexation as well (Zajacz et al., 2010, 2011; Pokrovski et al., 2015). Porphyry deposits are classically thought to be related to relatively oxidized parental magmas with much of the reduced S precipitated in the hydrothermal system being produced by disproportionation of magmatic SO₂ to sulphide and sulphate (e.g. Chambefort et al., 2008; Richards, 2011, 2015). Yet, the ubiquitous presence of magmatic sulphides in the source magmas of several large porphyry deposits led many researchers to propose

* Corresponding author.

E-mail addresses: carter.grondahl@mail.utoronto.ca (C. Grondahl), zajacz@es.utoronto.ca (Z. Zajacz).

that sulphides may play an essential role in porphyry genesis, either by pre-concentration of ore metals at lower or upper crustal levels (Halter et al., 2002a; Richards, 2009; Nadeau et al., 2010; Wilkinson, 2013), or by allowing efficient transfer of ore metals from mafic to felsic parts of magma reservoirs (Mungall et al., 2015). Others argued for the limited role of magmatic sulphides in porphyry deposit genesis either by attributing them only a temporary metal repository role (Audétat and Pettke, 2006; Zajacz et al., 2012a) or proposing that they may only affect Au and platinum group elements (PGE) potential (Cocker et al., 2016).

The giant Bingham Canyon porphyry Cu–Mo–Au deposit in Utah is an ideal system to test the significance of these processes. It has been in the focus of research, and the deposit itself has been extensively studied (e.g. Waite et al., 1997; Landtwing et al., 2010; Seo et al., 2012). It is one of the world's largest porphyry deposits with an estimated 55.9 Mt Cu, 2,600 t Au, and 1.4 Mt Mo (Steinberger et al., 2013). While the hydrothermal evolution of the deposit is well-understood, there are still open questions regarding the associated magmatism. Past studies using ore-fluid Pb isotopes (Pettke et al., 2010) and whole-rock compositions (Waite et al., 1997; Maughan et al., 2002) suggested the derivation of the Bingham magmatic suite from a Proterozoic-metasomatized mantle source which underwent partial melting in the Eocene. A number of studies proposed that the mixing of melanephelinite with more felsic trachytic or rhyolitic magmas produced the ore-related shoshonitic-latic magmas, with the melanephelinites donating the bulk of the ore metals and sulphur. Therefore, this mixing event was proposed to be a key to the formation of the deposit (Waite et al., 1997; Hattori and Keith, 2001; Maughan et al., 2002; Zhang and Audétat, 2017). Stavast et al. (2006) argued that sulphide and metal zoning in a shallow dyke adjacent to the deposit are analogues for large scale magmatic processes whereby magmatic sulphides donate their ore metal content to exsolving ore fluids. In contrast, Core et al. (2006) described small mafic enclaves from the adjacent unmineralized Last Chance intrusive stock containing bornite and chalcopyrite, suggesting that the magmatic system associated with the deposit evolved at high oxygen fugacity (fO_2) in the absence of pyrrhotite, and was characterized by particularly high Cu concentrations.

In this study we present silicate melt inclusion (SMI) data from the volcanic sequence that is nearly coeval with the deposit formation, with primary focus on the ore-related and ore-contemporaneous latitic magmatism. These data are used to assess critical processes during the genesis and evolution of the Bingham magmas that ultimately contributed to the generation of this giant ore deposit. Concentrations of Cu, Au, Mo, S, Cl and numerous other major and trace elements were reconstructed along the liquid line of descent and are used in combination with whole-rock and phenocryst compositions to address many of the above-described open questions regarding magmatic controls on porphyry ore genesis.

2. Methods

2.1. Sampling

The Bingham Canyon deposit is located in the Oquirrh Mountains in Utah, USA, approximately 30 km south-west of Salt Lake City.

Volcanic rocks, nearly coeval with the main ore-forming episode (e.g. Maughan et al., 2002), were collected from the Rose and Yellow Fork Canyons area, approximately 5 km south of the Bingham Canyon deposit (Fig. 1). Thick sections were made from about 60 samples with well-preserved phenocrysts. Subsequently, samples with clinopyroxene and plagioclase containing relatively large

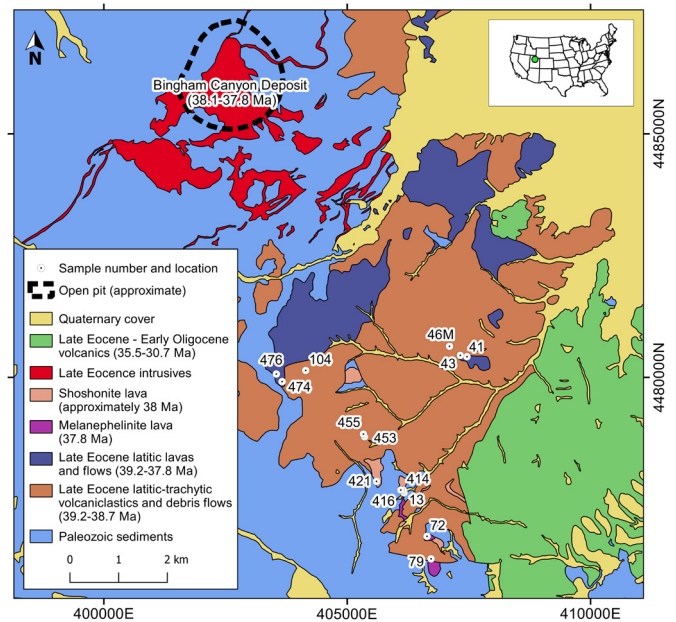


Fig. 1. Geologic map showing sample locations in the ore-contemporaneous volcanic package. Bedrock geology is compiled from Biek et al. (2005), Clark et al. (2012, 2016), and our fieldwork. White areas are under modern cover. Deposit age from von Quadt et al. (2011), volcanic ages from Biek et al. (2005) and references therein.

(>20 μm) intact SMI were selected for further investigation. Detailed petrographic descriptions of selected samples can be found in Appendix A.

2.2. Experimental methods

To allow electron probe microanalysis (EPMA) of the SMI, the inclusions had to be re-melted and quenched to a homogeneous glass. Following the failure to achieve homogenization at atmospheric pressures even at temperatures exceeding 1050 °C in a Linkam TS1400XY microscope heating stage, we homogenized SMI under confining pressure to prevent or minimize the loss of volatiles during the heating experiment. This was performed in a Mo–Hf carbide pressure vessel assembly in argon pressure medium at 1000 °C and 200 MPa for 1–1.5 h on 3.2 mm diameter cylindrical cores drilled from rock samples. After rapid quenching, the cores were sliced, mounted, and polished to allow EPMA of exposed homogenized SMI. Volatile constituents such as H₂O, CO₂, S and Cl could be lost from a SMI during reheating by fluid leakage developing due to the internal overpressure, and H₂O may also be lost by H diffusion (Lowenstern, 1995). The application of external pressure should have effectively prevented leakage, thus the measured S and Cl concentrations in the SMI are likely representative of the originally trapped melt composition. Whole-rock compositions were obtained on glasses fused from rock powders in high-purity graphite crucibles in an induction furnace. More details of this procedure and all applied experimental techniques can be found in the Appendix C.

2.3. Analytical techniques

Major element concentrations in minerals and homogenized SMI were determined by EPMA. The electron beam was defocused as much as the size of the SMI allowed (i.e. 5–20 μm) and 7–10 nA beam current was used. The Na signal was online monitored, and data from analyses suffering from Na-migration were not used. Sulphur and Cl signals were collected subsequently at 70 nA beam current and 40 s peak counting times. Additional details on the EPMA analyses can be found in Appendix C.

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