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Volcanic–plutonic connections and metal fertility of highly evolved magma systems: A case study from the Herberton Sn–W–Mo Mineral Field, Queensland, Australia

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A B S T R A C T

Understanding the connection between the highly evolved intrusive and extrusive systems is essential to explore the evolution of high silicic magma systems, which plays an important role in discussions of planetary differentiation, the growth of continents, crustal evolution, and the formation of highly evolved magma associated Sn–W–Mo mineral systems. To discern differences between “fertile” and “non-fertile” igneous rocks associated with Sn–W–Mo mineralization and reveal the genetic links between coeval intrusive and extrusive rocks, we integrate whole rock geochemistry, geochronology and Hf isotope signatures of igneous zircons from contemporaneous plutonic and volcanic rocks from the world-class Herberton Mineral Field of Queensland, Australia. The 310–300 Ma intrusive rocks and associated intra-plutonic W–Mo mineralization formed from relatively oxidized magmas after moderate degrees of crystal fractionation. The geochemical and isotopic features of the coeval volcanic succession are best reconciled utilizing the widely-accepted volcanic–plutonic connection model, whereby the volcanic rocks represent fractionated derivatives of the intrusive rocks. Older intrusions emplaced at 335–315 Ma formed from relatively low fO_2 magmas that fractionated extensively to produce highly evolved granites that host Sn mineralization. Coeval volcanic rocks of this suite are compositionally less evolved than the intrusive rocks, thereby requiring a different model to link these plutonic–volcanic sequences. In this case, we propose that the most fractionated magmas were not lost to volcanism, but instead were effectively retained at the plutonic level, which allowed further localized build-up of volatiles and lithophile metals in the plutonic environment. This disconnection to the volcanism and degassing may be a crucial step for forming granite-hosted Sn mineralization.

The transition between these two igneous regimes in Herberton region over a ~30 m.y. period is attributed to a change from an early compressive tectonic environment with a thickened crust, to conditions of crustal thinning and lithospheric extension due to progressive slab rollback. Such tectonic transitions may provide favorable conditions for intrusion-related mineralization. Given the common occurrence of volcanic and plutonic rocks associated with Sn–W–Mo mineralization worldwide, we suggest that a combined understanding of temporal tectonic evolution and plutonic–volcanic connections can assist in assessment of regional-scale mineralization potential, which in turn can aid strategies for future ore deposit exploration.

1. Introduction

Only a tiny proportion of the Earths' magmatic rocks host economically significant mineralization, so establishing decisive distinctions between metallo-genetically “fertile” and “non-fertile” magmas is of enormous benefit to mineral exploration. In recent years, substantial progress has been made in recognizing and understanding the genesis of intrusive rocks that are directly associated with porphyry Cu ± Au mineralization (Richards, 2009; Sillitoe, 2010; Loucks, 2014), which in turn has allowed formulation of fertility indicators (Loucks, 2014). Cu ± Au porphyry deposits tend to be associated with moderately fractionated, hydrous and oxidized magmas from arc settings (Sillitoe, 2010), Sn ± W mineralization is also primarily associated with magmatic rocks, but these mineralization systems have not been the subject of significant study in recent years, particularly in relation to magma fertility. Ishihara (1981), and Blevin and co-authors (Blevin and Chappell, 1992; Blevin et al., 1996; Blevin, 2004) recognized

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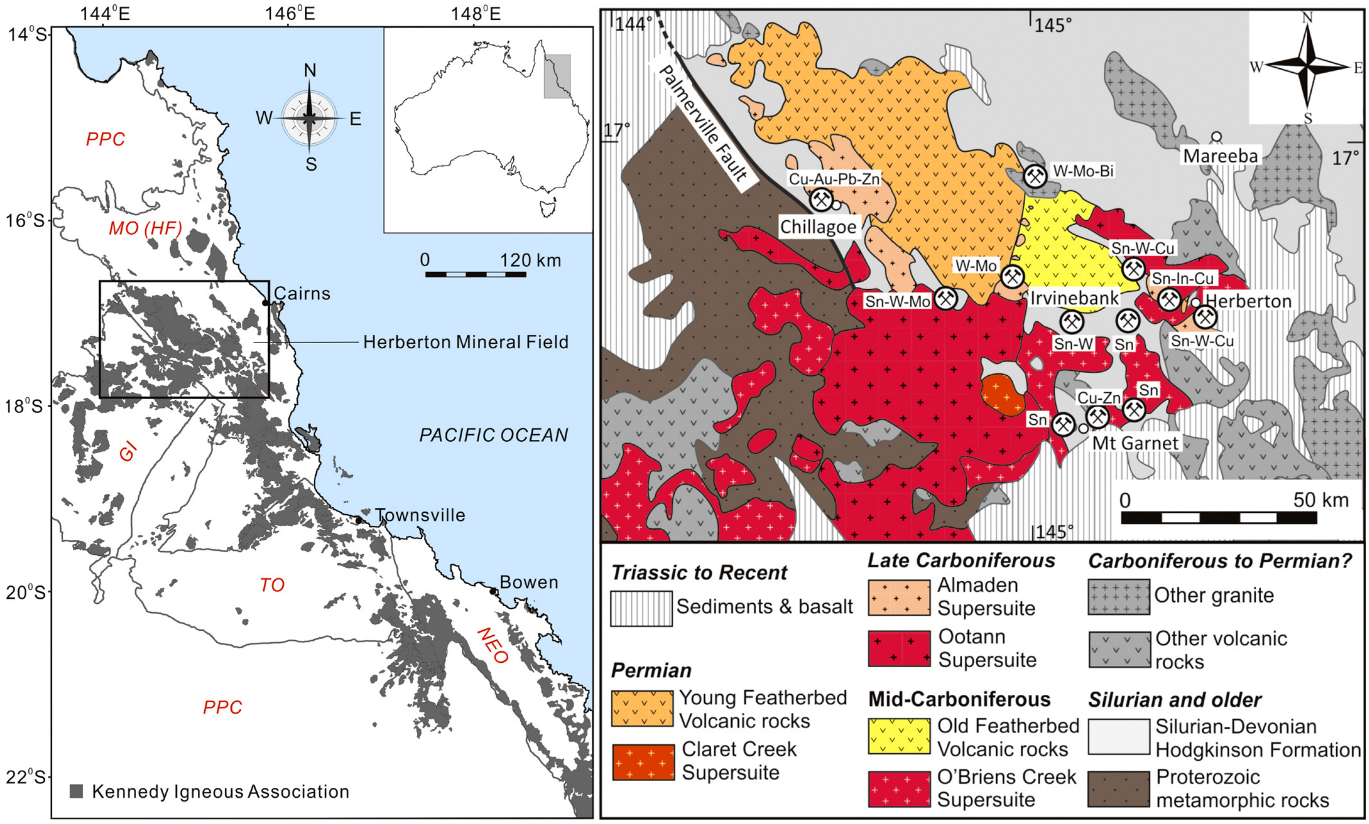

Fig. 1. Distribution of Carboniferous–Permian volcanic and granitic rocks of the Kennedy Igneous Association in the northeast Queensland, Australia (left; modified from Champion and Bultitude, 2013) and, the simplified geological map of the Herberton Sn–W–Mo Mineral Field showing the spatial distribution of granitoids, volcanic rocks and mineral deposits (right; modified from Black et al., 1978). MO = Mossman Orogen; HF = Hodgkinson Formation; NEO = New England Orogen; TO = Thomson Orogen; GI = Georgetown Inlier; PPC = Post Permian Cover.

that redox state and crystal fractionation have strong influences on the evolution of granitic magmas and their resulting mineralization styles, with Sn–W–Mo mineralization favored in relatively reduced, highly fractionated granite systems. For this reason, studies of magma fertility associated with Sn $\pm$ W mineralization tend to focus on granitic rocks, rather than any associated volcanic rocks, despite the fact that volcanic rocks are widespread in Sn $\pm$ W mineral fields and may be used as indicators for mineralization at depth provided that genetic links between the plutonic and volcanic rocks can be demonstrated. Herein lies a significant limitation: Although models linking plutonic and volcanic rock suites of intermediate to felsic, calc-alkaline affinity are well established (Bachmann et al., 2007), the links between volcanic and plutonic rocks produced in highly fractionated and reduced magmatic systems remain poorly understood.

To investigate the relationship between granitoids and volcanic rocks associated with Sn–W–Mo mineralized magma systems, we examined one of the world's best-known Sn–W–Mo districts: the Herberton Mineral Field (HMF) of North Queensland, Australia. The HMF has previously been studied in relation to the geology, petrogenesis and magma fertility of the ore-associated granites (Blevin et al., 1996; Champion and Bultitude, 2013) and regional W–Sn metallogeny (Taylor, 1978). In this study, we examine extrusive and intrusive rocks with close spatial and temporal links to Sn–W–Mo mineralization, with the aims of: (1) investigating the volcanic–plutonic connection in a highly evolved felsic magma system; (2) assessing the dynamic tectonic conditions responsible for magma evolution with time, and; (3) identifying potential fertility indicators from volcanic rocks associated with granite-related Sn–W–Mo mineralization.

2. Geological setting

The Kennedy Igneous Association is a collection of Carboniferous to Permian aged felsic plutonic and volcanic units that form a ~600 km long by 70–100 km wide belt in northeastern Queensland, Australia. The granitoids and volcanic rocks make up about 70% of basement exposure in the region, and therefore represent the most widespread and voluminous magmatic event of northeast Queensland (Champion and Bultitude, 2013). The igneous rocks of the Herberton region represent the largest exposure of the Kennedy Igneous Association (Fig. 1). Based on studies of basement rocks and a deep crustal seismic reflection survey Korsch et al. (2012) had identified four seismic provinces (Abingdon, Georgetown, Agwanin and Greenvale) of expected Proterozoic age, that form the lower to middle crust of north-east Queensland. In the Herberton region, these basement terranes are overlain by the Hodgkinson Province (Fig. 1), which consists of Silurian–Devonian siliciclastic and carbonate sedimentary and mafic volcanic rocks. This variety of basement rock units may locally provide crustal sources of different age for magma generation.

The Kennedy Igneous Association is thought to have developed as part of an active continental margin with a west dipping subduction zone (Withnall and Henderson, 2012). Tectonic models suggest that the emplacement of the Kennedy Igneous Association can be divided into 2 stages: 1) emplacement of Early Carboniferous intrusions into sedimentary rocks of the Hodgkinson Province. These intrusions were possibly derived from partial melting of variably-aged crustal sources during crustal thickening (Vos et al., 2007); 2) crustal melting due to basaltic magma underplating during slab rollback from the Late Carboniferous to Early Permian (Murgulov et al., 2007; Champion and Bultitude, 2013).