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Post-collisional alkaline magmatism as gateway for metal and sulfur enrichment of the continental lower crust

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Abstract

Mafic and ultramafic magmas that intrude into the lower crust can preserve evidence for metal and sulfur transfer from the lithospheric mantle into the lower continental crust. Here we focus on a series of ultramafic, alkaline pipes in the Ivrea Zone (NW Italy), which exposes deeply buried (6–11 kbar), migmatitic metasedimentary rocks intruded by voluminous basaltic magmas of the Mafic Complex, a major crustal underplating event precisely dated via U/Pb CA-IDTIMS on zircon at 286.8 ± 0.4 Ma. The ultramafic pipes postdate the Mafic Complex and from 100 to 300 m wide cumulate-rich conduits. They are hydrated and carbonated, have unusually high incompatible element concentrations and contain blebby and semi-massive Ni-Cu-PGE sulfide mineralisation. The sulfides occur as coarse intergranular nodules (>10 mm) and as small intragranular blebs (<1 mm) hosted in olivine, and have homogeneous, mantle-like $\delta^{34}S$ (+1.35 ± 0.25‰). This homogeneity suggests that the pipes reached sulfide supersaturation without addition of crustal sulfur, and that the $\delta^{34}S$ signature is representative of the continental lithospheric mantle. One of the pipes, the 249 Ma Valmaggia pipe, carries a very distinctive Sr-Nd-Hf-Pb isotopic composition in its core ($^{87}Sr/^{86}Sr$ 0.70250, $\varepsilon_{Nd\text{-}18}$, $\varepsilon_{Hf\text{-}18}$, $^{206}Pb/^{204}Pb$ 16.0, $^{207}Pb/^{204}Pb$ 15.16, $^{208}Pb/^{204}Pb$ 35.87), very different from the margin of this pipe and from other pipes that have higher $^{87}Sr/^{86}Sr$, ε_{Nd} and $^{206}Pb/^{204}Pb$. The unusual isotopic composition of the Valmaggia pipe requires a source with long-term (2500–1500 million years) U-, Th- and Rb-depletion and LREE enrichment. Such compositions are found in Late Archean/Early Proterozoic granulites and lower crustal xenoliths. We suggest that the unusual isotopic composition of the Valmaggia pipe reflects contamination of the mantle source of the pipe with a crustal component that is neither represented in the local Paleozoic crust nor in the isotopically anomalous hydrated mantle inferred as the source of the large-volume mafic underplate that formed the Mafic Complex. During post-collisional gravitational collapse of the Variscan Orogen, this source produced the alkaline, metal (Ni, Cu, PGE)- and volatile (H_2O, CO_2, S)-rich mafic–ultramafic magma that formed the deep-crustal intrusion at Valmaggia. U/Pb dating of other chemically and geologically comparable pipes in the area shows that this process was active over at least 40 Ma. The Ivrea pipes illustrate how the lower continental crust can be fertilised with mantle-derived metals and volatiles, which are available for later remobilisation into upper-crustal ore systems. World-class mineral deposits along the margins of

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lithospheric blocks may thus be the result of both favourable crustal architecture (focussing of magmas and fluids) and localised volatile and metal enrichment of the lower crust related to mantle-derived hydrous metasomatism.

Keywords: Continental lithospheric mantle; Lower continental crust; Ni-Cu-PGE; Magma emplacement; Ivrea zone

1. INTRODUCTION

The lower continental crust represents a chemical and physical threshold between contrasting Earth reservoirs (Rudnick and Fountain, 1995). It is often thought that during the evolution of a geological terrain, this rheological layer acts as an impermeable barrier that prevents mixing and physical interaction between the subcontinental lithospheric mantle and the overlying continental crust (Kelemen and Aharonov, 1998). However, during specific tectono-magmatic processes, the lower crust has the potential to behave as a gateway for the injection of mantle-derived melts into the continental crust. In some instances, there may be cargoes of volatiles (H_2O, CO_2, S) associated with the magmas that can fertilise the largely anhydrous lowermost parts of the crust (Locmelis et al., 2016). These magmas may form localised nickel (Ni)-copper (Cu)-platinum group element (PGE = Ru, Rh, Pd, Os, Ir, Pt) sulfide mineralisation in the lower crust (e.g. Bagas et al., 2016). Alternatively, magmas may pond in the lower crust, fractionate, and form the roots of porphyry Cu systems, which would ultimately be emplaced in the upper crust (Richards, 2011; Loucks, 2014; Lu et al., 2015).

Numerous methods have been employed to decipher the emplacement dynamics of magmatic systems through the lithosphere, including geophysical, petrological, textural and geochemical approaches (e.g. Barnes et al., 2016 and references therein). Many authors have observed that magma transport preferentially occurs through the transfer of small volume magma batches with a rapid rate of transport, as opposed to less frequent transport of larger magma volumes that require storage in large crustal reservoirs for prolonged periods of time (e.g. Zellmer and Annen, 2008; Menand, 2011). Mass transfer via the emplacement of small but frequent magma batches has been documented in collisional zones, where differentiated plutons that intrude the upper crust locally contain significant gold (Au) and Cu concentrations associated with porphyry systems (Loucks, 2014). However, the style of magma emplacement, as well as the mechanism, rate and dynamics of metal and volatile transfer from the locally enriched lithospheric mantle into the base of the continental crust is poorly constrained (Griffin et al., 2009), largely because few places on Earth provide direct access to the deepest parts of the continental crust.

Here, we investigate a series of well-preserved and rare examples of mafic-ultramafic intrusions containing Ni-Cu-PGE sulfide mineralisation of variable texture and composition emplaced at the base of the continental crust in the Ivrea Zone, Italy (Fig. 1; Garuti et al., 1986, 1990, 2001; Garuti, 1993; Zaccarini et al., 2014). These intrusions provide new insights into the rate and dynamics of volatile transfer from the subcontinental lithospheric mantle into the lower continental crust. Further, we examine the poorly constrained magmatic processes that lead to the formation of Ni-Cu-PGE sulfide mineralisation in the deep continental crust; this is potentially an important reservoir of metals and sulfur for subsequent magmatic events. The Ivrea Zone exposes the lower section of the Southern Alpine crust (Schmid, 1993), which was mainly deformed and metamorphosed during the 360–310 Ma Variscan Orogeny as a result of the collision between Laurussia and Gondwana (and the closure of the intervening Rheic Ocean), during formation of the Pangea supercontinent. The Ivrea Zone was subsequently only marginally reworked during the Alpine Orogeny from ca. 100 Ma onwards (e.g. Schmid, 1993), when the lower continental crust section that is the focus of this study was tilted to sub-vertical and exhumed (e.g. Garuti et al., 1980).

The setting where these deep mineralised intrusions were emplaced is currently contentious. Whereas Garuti et al. (2001) suggested that they represent the last mantle-derived melts associated with an intra-cratonic underplating event, Locmelis et al. (2016) indicated that these intrusions formed from partial melting of the metasomatised continental lithospheric mantle following post-collisional gravitational collapse of the Variscan Orogen. On the basis of new stable and radiogenic isotope data, which were collected both in-situ on sulfides and zircon grains, respectively, as well as by whole-mineral analysis, with high-precision fluorination and isotope dilution techniques, this study illustrates the important role of deep mineralised magmatic systems in the transfer of volatiles and metals from the metasomatised continental lithospheric mantle to the base of the continental crust. High-precision U/Pb geochronology is used to temporally resolve discrete magmatic pulses in order to test hypotheses on the rate and duration of sulfur- and metal-bearing magmatism. We suggest that the processes illustrated here provide a first-order explanation for the empirical observation that giant mineral deposits commonly form along the margins of lithospheric blocks (Mole et al., 2013).

2. GEOLOGICAL BACKGROUND

The Ivrea Zone exposes the lower section of the Southern Alpine crust, which was deformed and metamorphosed during the Variscan Orogeny. This is subdivided in three main stages (e.g. Schulmann et al., 2014 and references therein): (1) the Eo-Variscan oceanic to continental subduction from 420 to 380 Ma, which is marked by high-pressure metamorphism; (2) the Meso-Variscan collision stage from 360 to 310 Ma, which results from the tectonic accretion of terranes mainly derived from the Gondwana continental