Lithos 244 (2016) 74–93

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Sulfur and metal fertilization of the lower continental crust

Marek Locmelis [a,b,*], Marco L. Fiorentini [b], Tracy Rushmer [c], Ricardo Arevalo Jr. [a], John Adam [c], Steven W. Denyszyn [b]

[a] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[b] Centre for Exploration Targeting and ARC Centre of Excellence for Core to Crust Fluid Systems, School of Earth and Environment, The University of Western Australia, Perth, Australia
[c] ARC Centre of Excellence for Core to Crust Fluid Systems, Department of Earth and Planetary Sciences, Macquarie University, Sydney, Australia

ARTICLE INFO

Article history:
Received 12 August 2015
Accepted 19 November 2015
Available online 7 December 2015

Keywords:
Mantle–crust interaction
Volatile and metal mass transfer
Lamproite magmatism
Magmatic sulfide deposits
Ivrea-Verbano Zone
Zircon U–Pb dating

ABSTRACT

Mantle-derived melts and metasomatic fluids are considered to be important in the transport and distribution of trace elements in the subcontinental lithospheric mantle. However, the mechanisms that facilitate sulfur and metal transfer from the upper mantle into the lower continental crust are poorly constrained. This study addresses this knowledge gap by examining a series of sulfide- and hydrous mineral-rich alkaline mafic–ultramafic pipes that intruded the lower continental crust of the Ivrea–Verbano Zone in the Italian Western Alps. The pipes are relatively small (<300 m diameter) and primarily composed of a matrix of subhedral to anhedral amphibole (pargasite), phlogopite and orthopyroxene that enclose sub-centimeter-sized grains of olivine. The 1 to 5 m wide rim portions of the pipes locally contain significant blebby and disseminated Fe–Ni–Cu–PGE sulfide mineralization.

Stratigraphic relationships, mineral chemistry, geochemical modeling and phase equilibria suggest that the pipes represent open-ended conduits within a large magmatic plumbing system. The earliest formed pipe rocks were olivine-rich cumulates that reacted with hydrous melts to produce orthopyroxene, amphibole and phlogopite. Sulfides precipitated as immiscible liquid droplets that were retained within a matrix of silicate crystals and scavenged metals from the percolating hydrous melt. New high-precision chemical abrasion TIMS U–Pb dating of zircons from one of the pipes indicates that these pipes were emplaced at 249.1 ± 0.2 Ma, following partial melting of lithospheric mantle pods that were metasomatized during the Eo-Variscan oceanic to continental subduction (~420–310 Ma). The thermal energy required to generate partial melting of the metasomatized mantle was most likely derived from crustal extension, lithospheric decompression and subsequent asthenospheric rise during the orogenic collapse of the Variscan belt (<300 Ma).

Unlike previous models, outcomes from this study suggest a significant temporal gap between the occurrence of mantle metasomatism, subsequent partial melting and emplacement of the pipes. We argue that this multi-stage process is a very effective mechanism to fertilize the commonly dry and refractory lower continental crust in metals and volatiles. During the four-dimensional evolution of the thermo-tectonic architecture of any given terrain, metals and volatiles stored in the lower continental crust may become available as sources for subsequent ore-forming processes, thus enhancing the prospectivity of continental block margins for a wide range of mineral systems.

1. Introduction

The Ivrea–Verbano Zone (IVZ) in northwest Italy (Fig. 1) represents a section of continental crust and lithospheric mantle that was uplifted during the Alpine orogeny (Garuti et al., 1980; Mehnert, 1975; Rutter et al., 1993). Because of its exposure, it is an excellent natural laboratory to study the formation and evolution of the Earth's lower continental crust and continental lithospheric mantle. Thus, previous studies of the IVZ have contributed significantly to the understanding of the dynamic evolution of lower crustal and upper mantle rocks (e.g. Barboza et al., 1999; Henk et al., 1997; Mehnert, 1975; Rivalenti et al., 1981; Sills and Tarney, 1984; Quick et al., 1994; Zingg, 1983).

Despite the wealth of previous work, only little research has been done on a series of mafic–ultramafic alkaline pipe-like intrusions that intruded into the lower stratigraphic sections of the IVZ (Fiorentini and Beresford, 2008; Fiorentini et al., 2002; Garuti et al., 2001). These small intrusions (<300 m diameter) consist of amphibole-rich peridotites and hornblendites, with minor segregations of more felsic composition and host blebby and disseminated magmatic sulfide mineralization along their outer rims (Garuti et al., 2001). They have previously been interpreted as ultramafic intrusions derived from a depleted peridotite source that was metasomatically enriched in alkalis, Cu, S and platinum-group elements (Fiorentini and Beresford, 2008;

* Corresponding author at: NASA Goddard Space Flight Center, Greenbelt, MD, USA.
E-mail address: Marek.Locmelis@nasa.gov (M. Locmelis).

http://dx.doi.org/10.1016/j.lithos.2015.11.028
0024-4937/

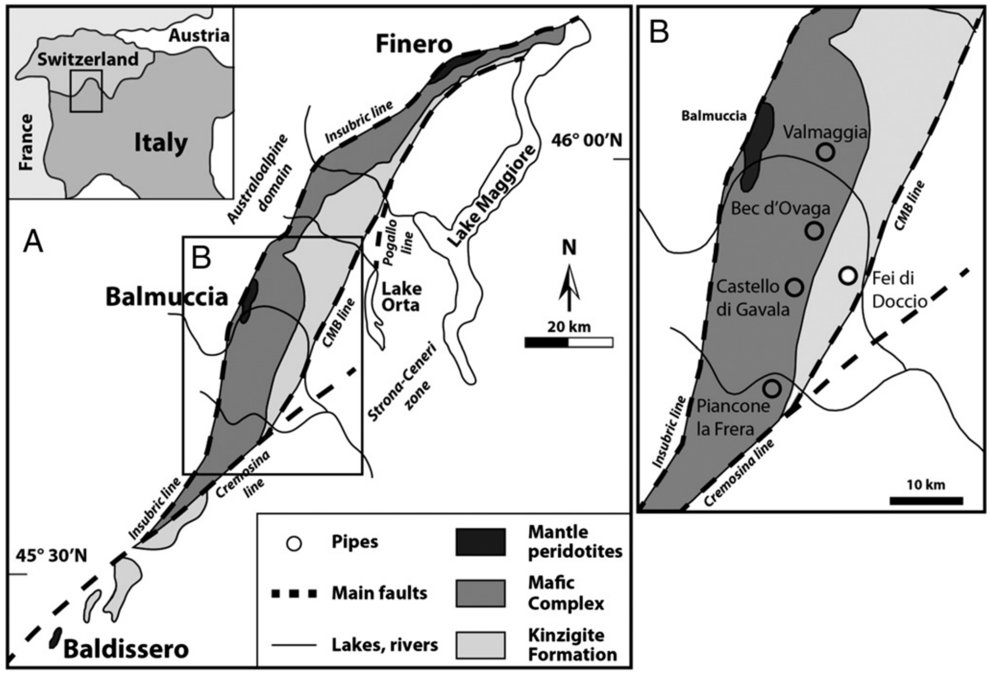

Fig. 1. Simplified geological map of the Ivrea–Verbano Zone showing the location of the pipes. Modified from Fiorentini and Beresford (2008).

Garuti et al., 2001). However, relatively little work has been done on the nature of the parental magmas of the pipes and their crystallization history.

This study integrates new electron microprobe and laser ablation ICP-MS data for individual pipe minerals with both new and previously-published bulk-rock analyses, to investigate (i) the crystallization history of the pipes and the nature of their parental magmas; (ii) the tectonic environment enabling the pipe formation; and (iii) the potential of such intrusions to produce economically important deposits of Ni, Cu and platinum-group elements (PGE). The results are used to reflect on the mechanisms that control sulfur and metal mass transfer between the upper mantle and lower continental crust. We also establish a geodynamic framework for the emplacement of the pipes, supported by new high-precision U–Pb zircon geochronology on the Valmaggia pipe.

2. Geological background

2.1. Ivrea–Verbano Zone

The Ivrea–Verbano Zone outcrops subvertically over ~150 × 15 km, extending from northwest Italy to southern Switzerland (Fig. 1). To the west and northwest, the Canavese segment of the Insubric Line separates the IVZ from the Austroalpine Domain (Schmid et al., 1987). To the south and southeast, the Cremosina, Cossato–Mergozzo–Brissago and Pogallo Lines separate the IVZ from the Strona–Ceneri Zone (Boriani et al., 1990).

Three main lithological formations exist: (i) the Mafic Complex, (ii) the Kinzigite Formation, and (iii) the mantle peridotites (Fig. 1). The Mafic Complex, formed from mantle-derived mafic magmas underplating the basement of the Southern Alps, can be subdivided into three units: the Layered Series (or Cyclic Units), the Main Gabbro and the Diorite Unit (e.g. Garuti et al., 2001; Pin and Sills, 1986; Rivalenti et al., 1984; Sinigoi et al., 1994). The Layered Series is the lowermost unit and consists of a sequence of layered mafic–ultramafic rocks with intercalated septa of strongly migmatized metasediments (Garuti et al., 2001; Rivalenti et al., 1984). It is overlain by the Main Gabbro, which grades upwards into the Diorite Unit. A metasedimentary septum of up to 100 meters thick separates the Layered Series and the Main Gabbro, suggesting that the two formations represent two different intrusive events (Ferrario et al., 1982; Garuti et al., 2001). The Kinzigite Formation is in magmatic contact with the top of the Diorite Unit. It consists of a prograde metamorphic sequence of middle amphibolite-to-granulite facies rocks, primarily composed of metapelites intercalated with mafic meta-igneous rocks, marbles, quartzites and pegmatites (Bea and Montero, 1999; Schnetger, 1994).

The mantle peridotites occur within the Mafic Complex and are considered to represent obducted slices of the continental mantle that outcrop along the Insubric Line near Baldissero, Balmuccia and Finero (Fig. 1; Grieco et al., 2001; Hartmann and Wedepohl, 1993; Mazzucchelli et al., 2010; Schaltegger et al., 2015; Shervais and Mukasa, 1991; Wang et al., 2013; Wang and Becker, 2015; Zanetti et al., 1999). The peridotites have undergone different degrees of partial melting and metasomatism shown by melt extraction modeling using major and minor element compositions complemented by Nd and Sr isotopic data (Hartmann and Wedepohl, 1993). Most prominently, highly refractory major element compositions and distinct incompatible trace element enrichments in the amphibole- and phlogopite-bearing peridotite at Finero have been interpreted to reflect metasomatism of depleted peridotite by water-rich fluids derived from dehydration and melting of subducted sediments and oceanic crust (Exley et al., 1982; Hartmann and Wedepohl, 1993; Zanetti et al., 1999).

2.2. Pipe-like bodies

Five pipes are known to exist in the IVZ. However, due to dense vegetation and difficult terrain in the area, it is possible that more pipes outcrop, but are yet to be discovered. Four pipes are hosted within the Main Gabbro of the Mafic Complex at the localities of Bec d'Ovaga, Castello di Gavala, Valmaggia, and Piancone la Frera (Fig. 1). One pipe, at Fei di Doccio, is hosted within the Kinzigite Formation. No pipes have been found inside the Layered Series or the Diorite Unit. Due to poor exposure, the geometries of the pipes and their relationship to the host rocks are primarily derived from abandoned underground mines that were mined for Fe and Ni until the end of World War 2 (Fiorentini et al., 2002).

The pipes occur as small discordant intrusive bodies up to 300 m in diameter and mostly consist of hydrated peridotites and hornblendites