Earth and Planetary Science Letters 479 (2017) 108–119

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Disequilibrium growth of olivine in mafic magmas revealed by phosphorus zoning patterns of olivine from mafic–ultramafic intrusions

Chang-Ming Xing [a,b], Christina Yan Wang [a,b,*], Wei Tan [a,b]

[a] Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510460, China
[b] Guangdong Provincial Key Laboratory of Mineral Physics and Materials, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 18 August 2017
Accepted 6 September 2017
Available online xxxx
Editor: M. Bickle

Keywords:
olivine
phosphorus zoning
disequilibrium texture
igneous cumulate
mafic–ultramafic intrusion

ABSTRACT

Olivine from mafic–ultramafic intrusions rarely displays growth zoning in major and some minor elements, such as Fe, Mg and Ni, due to fast diffusion of these elements at high temperatures. These elements in olivine are thus not useful in deciphering magma chamber processes, such as magma convection, multiple injection and mixing. High-resolution X-ray elemental intensity mapping reveals distinct P zoning patterns of olivine from two mafic–ultramafic intrusions in SW China. Polyhedral olivine grains from lherzolite and dunite of the Abulangdang intrusion show P-rich dendrites similar to those observed in volcanic rocks. Rounded olivine grains from net-textured Fe–Ti oxide ores of the Baima layered intrusion have irregular P-rich patches/bands crosscut and interlocked by P-poor olivine domains. P-rich patches/bands contain 250 to 612 ppm P, much higher than P-poor olivine domains with 123 to 230 ppm P. In electron backscattered diffraction (EBSD) maps, P-rich patches/bands within a single olivine grain have the same crystallographic orientation, indicating that they were remnants of the same crystal. Thus, both P-rich patches/bands and P-poor olivine domains in the same grain show a disequilibrium texture and clearly record two-stage growth. The P-rich patches/bands are likely the remnants of a polyhedral olivine crystal that formed in the first stage, whereas the P-poor olivine domains containing rounded Ti-rich magnetite and Fe-rich melt inclusions may have formed from an Fe-rich ambient melt in the second stage. The complex P zoning of olivine can be attributed to the dissolution of early polyhedral olivine and re-precipitation from the Fe-rich ambient melt. The early polyhedral olivine was in chemical disequilibrium with the ambient melt that may have been developed by silicate liquid immiscibility in a crystal mush. Our study implies that olivine crystals in igneous cumulates with an equilibrium appearance may have experienced disequilibrium growth processes during slow cooling. Therefore, the crystallization sequence of mafic magmas based on textural relationships should be treated with caution.

1. Introduction

Olivine usually crystallizes as an early phase in mafic magmas. It has a simple chemical formula [$(Fe, Mg)_2SiO_4$] and diverse crystal habits including polyhedral, skeletal, dendritic, rounded and spongy shapes (Helz, 1987; Welsch et al., 2013), depending on different cooling rates and degrees of undercooling (Donaldson, 1976; Jambon et al., 1992; Faure et al., 2003, 2007; Faure and Schiano, 2004). Elucidation of the growth processes of olivine has important implications for crystal growth mechanisms, magma evolution and magma chamber processes (Sobolev et al., 2007; Pilbeam et al., 2013; Sanfilippo et al., 2014).

Olivine growth is diffusion-controlled during rapid cooling when it forms skeletal or dendritic crystals (Faure et al., 2003, 2007; Faure and Schiano, 2004). Dendrites are commonly preserved in olivine phenocrysts of volcanic rocks and are attributed to initially rapid growth of crystals, followed by slow ripening of hollow crystals during cooling (Milman-Barris et al., 2008; Welsch et al., 2013, 2014). On the other hand, olivine growth during slow cooling forms polyhedral crystals in an interface-controlled, tree-ring or spiral growth model (Burton et al., 1951; Faure and Schiano, 2005; Faure et al., 2007). Therefore, polyhedral olivine crystals in igneous cumulates usually lack growth zoning and sometimes show equilibrium textures such as 120° triple junction of grain boundaries. However, because of fast Mg–Fe diffusion in olivine and post-crystallization processes, e.g., trapped liquid

* Corresponding author at: Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510460, China.
E-mail address: wang_yan@gig.ac.cn (C.Y. Wang).

http://dx.doi.org/10.1016/j.epsl.2017.09.005

shift effect and sub-solidus re-equilibrium of cumulus minerals in magma chambers (Barnes, 1986; Pang et al., 2008), compositions of primary olivine in igneous cumulates may have been intensely modified. In addition, the mechanism of olivine growth during slow cooling has been relatively neglected and poorly understood. It is thus worthy to examine the growth process of olivine in a deep-seated magma chamber where rapid cooling is unlikely.

Experimental studies reveal that P has an extremely low diffusion rate compared with other elements in olivine (Spandler et al., 2007; Watson et al., 2015), and can be useful in deciphering the growth mechanism of olivine in igneous cumulates. In this paper, we present results of high-resolution X-ray elemental intensity mapping for polyhedral olivine from dunite and lherzolite of the Abulangdang ultramafic intrusion and rounded olivine from net-textured Fe–Ti oxide ores of the Baima layered intrusion in SW China. These results, in combination with those of EBSD mapping and *in situ* analyses by laser inductively coupled-plasma mass spectrometry (LA-ICP-MS), indicate that polyhedral olivine grains from dunite and lherzolite display P zoning patterns identical to those of olivine phenocrysts in volcanic rocks, whereas rounded olivine grains from net-textured Fe–Ti oxide ores have much more complex P zoning patterns that record unusual two-stage growth. This study thus provides new insights into the growth processes of olivine in mafic magmas and has important implications for magmatic processes through which Fe–Ti oxide-rich mafic–ultramafic intrusions formed.

2. Abulangdang and Baima intrusions in SW China

Both the Abulangdang and Baima intrusions in SW China are parts of the Emeishan large igneous province (LIP). The Emeishan LIP is believed to have been formed from a mantle plume at ∼260 Ma and covers an area of 7×10^5 km^2 from SW China to northern Vietnam (Li et al., 2017 and references therein) (Fig. 1a). The volcanic succession of the Emeishan LIP varies in thickness from several hundred meters to ∼5 km and is mainly composed of low-Ti and high-Ti flood basalts, with minor picrite, tephrite and basaltic andesite (Xu et al., 2001; Qi et al., 2008). There are numerous coeval mafic–ultramafic intrusions and granitic and syenitic plutons in the Emeishan LIP (Zhou et al., 2008; Shellnutt and Iizuka, 2012).

In the Panzhihua–Xichang (Panxi) district, flood basalts of the Emeishan LIP are spatially associated with mafic–ultramafic intrusions and granitic and syenitic plutons that are exposed by several NS-trending faults (Fig. 1b). The mafic–ultramafic intrusions constitute a mineralized belt about 300 km long and 10 to 30 km wide, forming the most important metallogenic district for Fe, Ti and V in China (Zhou et al., 2005). The Abulangdang intrusion is the only ultramafic intrusion in the Panxi region (Wang et al., 2014). The Panzhihua, Baima, Taihe and Hongge layered intrusions host world-class Fe–Ti-(V) oxide deposits, whereas some other small mafic–ultramafic intrusions have Ni–Cu-(PGE) sulfide mineralization (Fig. 1b).

2.1. Abulangdang ultramafic intrusion

The Abulangdang ultramafic intrusion is an elongate lopolith and covers an area of ∼7.6 km^2. It is a concentric body composed of an inner core of dunite (75 vol.%) surrounded by plagioclase-bearing lherzolite (15 vol.%) and olivine gabbro (10 vol.%) (Wang et al., 2014) (Fig. 1c). The intrusion was considered to have formed from high-Ti picritic magmas at a depth equivalent to pressure of 7 to 10 kbar (Wang et al., 2014).

The dunite consists of 85 to 95% olivine, 3 to 10% orthopyroxene, <5% clinopyroxene and <2% chromite. Polyhedral olivine crystals have grain sizes ranging from 0.2 to 2 mm and show well-developed 120° triple junction of grain boundaries (Fig. 2a). The lherzolite is composed of 50 to 85% olivine, 5 to 10% clinopyroxene, 5 to 15% orthopyroxene, 5 to 10% plagioclase and <3% chromite and <2% sulfide. Olivine crystals are euhedral to subhedral and vary in size from 0.2 to 5 mm. Some olivine grains are enclosed within clinopyroxene, typical of poikilitic texture (Fig. 2b). Fine-grained chromite crystals are commonly enclosed in olivine (Fig. 2b).

2.2. Baima layered intrusion

The Baima intrusion is ∼24 km long and 2 to 6.5 km wide, and contains a large Fe–Ti-(V) oxide deposit in the Panxi region (Fig. 1d). The layered sequence of the intrusion is ∼1,600 m thick and is divided into a lower zone and an upper zone (Liu et al., 2014a). The lower zone is ∼150 to 300 m thick and is mainly composed of troctolite, olivine clinopyroxenite and olivine gabbro and hosts ∼100 m-thick Fe–Ti oxide ore layers. The ore layers are composed of net-textured Fe–Ti oxide ores with 40 to 60% Fe–Ti oxides and disseminated ores with 20 to 40% Fe–Ti oxides (Liu et al., 2014a). The upper zone is up to ∼1,200 m in thickness and is composed of isotropic olivine gabbro, gabbro and apatite-bearing gabbro. These rocks usually contain <10% Fe–Ti oxides. The Baima intrusion is proposed to have formed from high-Ti basaltic magmas at a depth equivalent to pressure of 3 to 5 kbar (Shellnutt et al., 2009; Pang et al., 2010). The formation of Fe–Ti oxide ores in the lower zone is thought to be due to silicate liquid immiscibility during the crystallization of the intrusion (Liu et al., 2014b).

Net-textured Fe–Ti oxide ores consist of 40 to 60% Fe–Ti oxides, 30 to 35% olivine, <10% plagioclase, <5% clinopyroxene and <2% sulfide (Fig. 3a). Olivine grains from net-textured ores are commonly rounded or elliptical. They vary from 0.02 to 2 mm in diameter, and are isolated by interconnected matrix composed of Fe–Ti oxides and minor sulfides (Fig. 3a). Olivine grains do not show clear zonation under microscope or in backscattered electron (BSE) images. They contain rounded, Ti-rich magnetite (<200 μm in diameter) and occasionally polycrystalline inclusions (Figs. 3b, c and d). Previous 3-D X-ray CT scanning reveals that the Ti-rich magnetite and polycrystalline inclusions are spherical in shape and are entirely enclosed in olivine, and do not connect with interstitial Fe–Ti oxides (Liu et al., 2014b). The polycrystalline inclusions are mainly composed of Ti-rich magnetite, ilmenite, spinel and phlogopite with sporadic apatite, amphibole and sulfides (Fig. 3d; also see Liu et al., 2014b), and they were explained to be trapped Fe-rich melt inclusions (Liu et al., 2014b). Chlorite commonly occurs along the rims and fractures of olivine (Figs. 3a and b). Plagioclase commonly has an irregular outline and is commonly rimmed by amphibole (Fig. 3a).

3. Analytical methods

3.1. High resolution X-ray elemental intensity mapping using electron microprobe

High resolution X-ray elemental intensity mapping for Mg, Fe, Al, Cr, Ni, Ca and P were applied for olivine grains on carbon-coated thin sections. The X-ray mapping was carried out using a JEOL JXA-8230 electron microprobe at the Key Laboratory of Mineralogy and Metallogeny in Guangzhou Institute of Geochemistry (GIG), Chinese Academy of Sciences (CAS). The operation conditions of an accelerate voltage of 20 kV, a probe current of 300 nA and a beam size of 1 to 4 μm were adopted for mapping. Mg and Al were analyzed using a TAP crystal. Fe, Cr and Ni were analyzed using a LIF crystal. Ca was analyzed using a PET crystal. P was analyzed with a PETH crystal to strengthen X-ray intensity. Elemental Kα line was chosen for all elements during analyses. The