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Carbonate- and silicate-rich globules in the kimberlitic rocks of northwestern Tarim large igneous province, NW China: Evidence for carbonated mantle source

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ABSTRACT

We report carbonate- and silicate-rich globules and andradite from the Wajilitage kimberlitic rocks in the northwestern Tarim large igneous province, NW China. The carbonate-rich globules vary in size from 1 to 3 mm, and most have ellipsoidal or round shape, and are composed of nearly pure calcite. The silicate-rich globules are elliptical to round in shape and are typically larger than the carbonate-rich globules ranging from 2 to several centimeters in diameter. They are characterized by clear reaction rims and contain several silicate minerals such as garnet, diopside and phlogopite. The silicate-rich globules, reported here for the first time, are suggested to be related to the origin of andradite within the kimberlitic rocks. Our results show that calcite in the carbonate-rich globules has a high X_{Ca} (>0.97) and is characterized by extremely high concentrations of the total rare earth elements (up to 1500 ppm), enrichment in Sr (8521–10,645 ppm) and LREE, and remarkable depletion in Nd, Ta, Zr, Hf and Ti. The calcite in the silicate-rich globules is geochemically similar to those in the carbonate-rich globules except the lower trace element contents. Garnet is dominantly andradite ($And_{59.56–92.32}Grs_{5.67–36.03}Pyr_{0.36–4.61}Spe_{0–0.33}$) and is enriched in light rare earth elements (LREEs) and relatively depleted in Rb, Ba, Th, Pb, Sr, Zr and Hf. Phlogopite in the silicate-rich globules has a high $Mg^{\#}$ ranging from 0.93 to 0.97. The composition of the diopside is $Wo_{45.82–51.39}En_{39.81–49.09}Fs_{0.88–0.95}$ with a high $Mg^{\#}$ ranging from 0.88 to 0.95. Diopside in the silicate-rich globules has low total rare earth element (REE) contents (14–31 ppm) and shows middle REE- (Eu to Gd), slight light REE- and heavy REE-enrichment with elevated Zr, Hf and Sr contents and a negative Nb anomaly in the normalized diagram. The matrix of the kimberlitic rocks are silica undersaturated (27.92–29.31 wt.% SiO_2) with low Al_2O_3 (4.51–5.15 wt.%) and high CaO (17.29–17.77 wt.%) contents. The samples are characterized by incompatible element enrichment with high $(La/Yb)_N$ values (41–58) and remarkable negative anomalies in HFSEs (e.g. Ta, Zr, Hf). Our new data suggest that the carbonate-rich globule most likely crystallized at high-temperature and does not represent immiscible liquids, whereas the silicate-rich globules are related to carbonate-rich deuteric hydrothermal fluids during the later-stage of melt evolution. The fluids reacted with the surrounding silicate melts resulting in the formation of skarn minerals such as phlogopite, diopside and andradite. The presence of the carbonate-bearing globules indicates that the Wajilitage kimberlitic rocks are carbonate-rich and most likely derived from an enriched mantle with abundant carbonate. We correlate the carbonated mantle to metasomatism by the migration of deep-seated fluids (carbonate-rich) in response to the impingement of the early Permian mantle plume.

1. Introduction

Kimberlite magmas are volatile-rich, silica-poor ultrabasic magmas which are considered to be produced by small-degree mantle melts at depths of 150 km or greater (e.g. Coe et al., 2008; Nowell et al., 2004; Sparks et al., 2006). They are of great interest because of their deep mantle origin, carrying mantle xenoliths, and are sometimes host to diamonds (e.g. Agashev et al., 2008; Chalapathi Rao et al., 2011; Coe et al., 2008; Francis and Patterson, 2009; Mitchell, 1986; Sparks et al., 2006; Van Achterbergh et al., 2004). Evidence from the chemistry of kimberlite and from experimental petrology had emphasized the role of upper mantle CO_2 in the

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kimberlite generation (Hetman et al., 2004; Howarth et al., 2011; Kamenetsky et al., 2012; Mitchell et al., 2009; Sparks et al., 2009; Steenfelt et al., 2009). Carbonate is a common mineral in kimberlite (e.g. Howarth et al., 2011). As a result of frequent intense alteration and the potential contamination by crustal rocks, it is often quite difficult to demonstrate whether the carbonates are primary or secondary (Hayman et al., 2009). Nevertheless, carbonate globules or ocelli are considered as unequivocal evidence for primary carbonate precipitated from kimberlite magma, normally interpreted as a product of the liquid immiscibility or a result of crystallization (e.g. Clement, 1975, 1982; Clarke and Mitchell, 1975; Clement and Skinner, 1979; Downes et al., 2007; Haggerty and Fung, 2006; Mitchell, 1975, 1986, 1994).

Our recent investigations have led to the discovery of both carbonate-rich and silicate-rich globules in the kimberlitic rocks of the Wajilitage area, northwestern Tarim large igneous province (Fig. 1a and b). The silicate-rich globules are characterized by abundant andradite, in contrast to the mantle garnet (peridotite and kimberlite), which is dominantly Mg-rich, i.e. pyrope (e.g. Boyd et al., 2004; Hoal et al., 1994; Ionov et al., 2005; Lazarov et al., 2009; Schulze, 2003; Xia et al., 2012a). The silicate-rich globule and calcium-rich garnet in the kimberlitic rocks are rare, and thus offer crucial clues to the melt evolution in the later stage. In this paper, we present major and *in situ* trace element data of the minerals in the globules, and evaluate the origin of the globules in the context of evolution of kimberlitic melts. Based on these results, we attempt to provide some key constraints on the nature of the mantle source properties.

2. Geological setting

The Tarim Craton is located in northwestern China, surrounded by the Tianshan Mountains to the north, Kunlun Mountains to the southwest and the Altun Range to the southeast (Fig. 1b). The Tarim Craton occupies an area of ~600,000 km^2 and most of the surface is buried by the Taklamakan Desert (Tian et al., 2010). The Craton is predominantly composed of metamorphosed Precambrian crystalline basement and Phanerozoic sedimentary cover (Long et al., 2010; Zhang et al., 2013a). The basement rocks are mainly exposed in the Kuluktage and Aksu areas to the north, the Altyn Tagh in the southeast and the Tieklik and western Kunlun in the southwest (Zhang et al., 2013a and references therein). The Precambrian basement formed between the Archean and Neoproterozoic (Lu et al., 2008), and is considered to have been a part of the Columbia and Rodinia supercontinents (Ma et al., 2013a,b; Zhang et al., 2013a). The Phanerozoic strata are dominated by Ordovician to Neogene limestones, sandstones and volcano-sedimentary sequences (Guo et al., 2005; Jia, 1997; Tian et al., 2010; Zhou et al., 2009). The fundamental tectonic framework of the Tarim Craton was extensively modified by the Cenozoic deformation, which produced several uplifts and depressions (Fig. 1b; Jia, 1997). Systematic field geological studies, industrial (oil) drill core information and geophysical data reveal that about 300,000 km^2 continental flood basalt were erupted during 290–275 Ma with the average thickness >100 m (e.g. Li et al., 2011; Tian et al., 2010; Yang et al., 2005; Zhang et al., 2010a,b; Zhou et al., 2004, 2009). The major Permian thermal event has drawn much attention in recent years, and several models have been proposed including post-orogenic collapse (Liu et al., 2004; Xu et al., 2005), continental rift (Yang et al., 2007) and mantle plume (e.g. Xia et al., 2012b; Zhang et al., 2008; Zhou et al., 2004, 2009). Recently, the voluminous igneous units in Tarim indicate that it is the second major large igneous province (LIP) after the Emeishan LIP in China (e.g. Pirajno et al., 2009; Tian et al., 2010; Zhang et al., 2010a,b; Zhou et al., 2009).

The Wajilitage region is located about 40 km southeast from the Bachu county, in the northwestern part of the Tarim LIP (Fig. 1b). Although this region is relatively small (<10 km^2), it includes a series of intrusions, e.g., mafic–ultramafic complex, diabase dikes, nepheline-bearing syenites, kimberlitic dikes/pipes, and carbonatite dikes, dioritic dikes and lamprophyre dikes (Fig. 1b; Li et al., 2012; Yang et al., 2007; Zhang et al., 2008, 2013b). These rocks intruded into the Devonian strata, which are composed of metamorphosed clastic sequences, namely the Keziletag and Yimugangawu Formations from bottom upwards. According to the field geology and available geochemical and geochronological data, the sequence of formation of the igneous rocks in the Wajilitage region has been identified as: kimberlitic dikes/pipes → mafic–ultramafic complex and carbonatite dikes → diabase dikes and nepheline-bearing syenites → lamprophyre dikes, from 300 to 275 Ma (Li et al., 2011; Yang et al., 2005, 2007; Zhang et al., 2008, 2013b).

Until now, 6 pipes and 32 kimberlitic dykes have been identified in the northern part of the Wajilitage, with a general NWW–SEE trend (Fig. 2a). The pipes are elliptical to round in shape and the dimensions are variable, ranging from 1.7 m × 3.5 m to 5 m × 5 m. The dikes, generally 0.5–2 m in wide and 5–7 m long, intrude into the Devonian strata, but the actual length should be longer because of desert cover. These dikes and pipes were emplaced into the upper Devonian Keziletag Formations and were cut by diabase dykes (Fig. 2c). Sharp contacts as well as chilled margin with baking phenomenon were observed at the contact zone between the kimberlitic rocks and wall rocks (Fig. 2b). The rocks experienced variable degrees of weathering and are covered by Quaternary deposits.

3. Petrology

3.1. Petrography of Kimberlitic rocks

The Wajilitage kimberlitic rocks examined in this study exhibit porphyroclastic fragmental texture and are hybrid rocks composed of the xenoliths and the cement. The Proportions of xenoliths vary widely ranging from 10% to 30%. The xenoliths are dominated by mafic–ultramafic rocks such as clinopyroxenite (~80%), olivine-bearing clinopyroxenite (~10%) and peridotite (~5%), in contrast to the mantle xenoliths (Supplementary file 1a and b). The other xenoliths are crustal xenoliths such as sandstone and amphibolite but are present in low amounts (~5%, Supplementary file 1c). These xenoliths vary in size from 1 mm to several centimeters (>5 cm) and have sharply angular or rounded shapes. They are typically holocrystalline and fine- to medium-grained, and comprise dominantly clinopyroxene, olivine, minor amphibole and phlogopite in the mafic–ultramafic xenolith, amphibole in the amphibolite, and quartz and feldspar in the sandstone. The cement is grayish in hand specimen and contains high amounts of euhedral to rounded minerals (30 vol.%), which are dominated by clinopyroxene (30–40%), olivine (25–30%), phlogopite (10–15%), amphibole (5–10%) and apatite (5%, Supplementary file 1d, e, h and i). However, it is difficult to define as true porphyritic texture as these minerals are not all primary liquidus phases crystallizing from the kimberlitic magma. Some of them are xenocrysts related to the mafic–ultramafic xenoliths, particularly in the case of olivine, clinopyroxene and amphibole (Supplementary file 1e). In most instances the phenocrysts are small and euhedral relative to the xenocrysts and occur as primary minerals in the groundmass (Supplementary file 1g). Occasionally, primary phases occur in association with the xenocrysts or the earlier-crystallized silicates and their crystals are typically zoned, such as in the case of clinopyroxene and amphibole (Supplementary file 1h and i). Cheng et al.