Mineralogical characterization of peridotite xenoliths from the Los Tormos volcano (Calatrava volcanic field)

Caracterización mineralógica de los xenolitos peridotíticos del volcán Los Tormos (Campo de Calatrava)

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ABSTRACT

Peridotite xenoliths from the Los Tormos volcano (Calatrava volcanic field) provide significant information about the lithospheric mantle of Central Iberia. Studied samples are classified as spinel-bearing lherzolite, harzburgite and wehrlite. Chemical composition of olivine and two pyroxenes shows similar Mg# ranges, providing evidence of mineral equilibrium. Geothermobarometric estimates give depths in the spinel peridotite stability field (35-50 km, 10-15.2 kbar), and temperatures of 961-1185 °C. Major element mineral melting models in the lherzolite xenoliths record a low partial melting degree (up to 10%) although one harzburgite indicates a higher degree of melting (about 15%). The wehrlite sample could result from metasomatism by interaction with alkaline silica-under saturated melts that replaced primary lherzolite orthopyroxene. Similar estimated pressures for peridotite mineral equilibration and for clinopyroxene megacryst/phenocryst crystallization in the host nepheline suggest the formation of mantle magma chambers, where alkaline magmas entrained megacrysts (cumulates) and peridotite wall-rocks.

Key-words: peridotite xenoliths, megacrysts, partial melting, Calatrava volcanic field.

RESUMEN

Los xenolitos de peridotitas del volcán Los Tormos (campo volcánico de Calatrava) proporcionan información valiosa sobre el manto litosférico del centro de España. Se estima que provienen de profundidades de 35-50 km (10-15.2 kbar), equilibrados a temperaturas de 961-1185 °C, en el campo de estabilidad de peridotitas con espinela. Los modelos de fusión obtenidos a partir de la composición química de las minerales primarios de la peridotita (ortopiroxeno, clinopiroxeno y espinela) muestran un bajo grado de fusión parcial (hasta un 10%), aunque una harzburgita indica un mayor grado de fusión (cerca del 15%). El xenolito de wehrlita se interpreta como un tipo metasomatizado debido a la posible interacción con fundidos alcalinos sub saturados en silice que reemplazarían el ortopiroxeno primario de la lherzolita. La similitud entre las presiones estimadas para el equilibrio mineral de la peridotita y la cristalización de megacrísticos/fenocrísticos de clinopiroxeno en la nefelinita sugiere la formación de cámaras magmáticas mantelicas.

Palabras clave: xenolitos de peridotita, megacrísticos, fusión parcial, campo volcánico de Calatrava.

Introduction

Mantle xenoliths from alkaline volcanic fields provide valuable information about the subcontinental lithospheric mantle. In the Iberian Peninsula, three volcanic districts bring to the surface mantle xenoliths. Among them, the Neogene Calatrava volcanic field (CVF) outstandingly by a large number (>200) of volcanic vents, mostly strombolian cinder cones or maars (Ancochea, 1982). Recent literature about peridotite xenoliths has been focused in three of these volcanoes: El Palo (Bianchini et al., 2010), Cerro Pelado (Villaseca et al., 2010), and El Aprisco/La Nava maar (Villaseca et al., 2010; González-Jiménez et al., 2014; Lierfeld and Mattsson, 2015).

In some of the studied volcanoes, associated with the mantle xenoliths, abundant megacrysts of amphibole, clinopyroxene, and/or phlogopite, appear scattered among the pyroclastic deposits. They have been interpreted as evidence of magmatic chambers at mantle depths (e.g., Dorado et al., 2016). Moreover, departure from primitive mantle composition of some CVF peridotite xenoliths suggests retrofertilization by contrasted metasomatic agents (e.g., González-Jiménez et al., 2014).

This study adds a new volcanic outcrop of peridotite xenoliths in the CVF. The Los Tormos volcano is an olivine nephelinite scoria cone located near Pozuelo de Calatrava village (Ciudad Real). Scoria fragments of pyroclastic fall deposits contain peridotite xenoliths and megacrysts. The mineral chemistry study of this new peridotite xenolith sampling, coupled with previous geochemical data on the CVF mantle xenoliths, have allowed us a better characterization of the mantle beneath Central Iberia.

Sampling and petrographic characterization

Nine representative peridotite xenoliths and one clinopyroxene megacryst were selected for mineralogical characterization. The small size of these enclaves prevented a whole-rock geochemical study. Peridotites consist of varying proportions of olivine, orthopyroxene, clinopyroxene, and brown to green spinel. No metasomatic mineral phases have been found (e.g., phlogopite,
amphibole), although local reaction zones with the host olivine nepheline have been found. According to modal contents the peridotite xenoliths are classified as herzolite (n=6), harzburgite (n=2) and wehrlite (n=1). This compositional range is similar to those obtained in other CVF vents (Bianchini et al., 2010; Villaseca et al., 2010; González-Jiménez et al., 2014). The peridotites show a coarse- to medium-grained (>2mm), roughly equidimensional porphyrastic texture. One harzburgite sample shows porphyroclastic texture. Spinel has been found only in lherzolites, appearing as interstitial fine-grained crystals. Exsolution lamellae in both pyroxenes are common. We have also studied one clinopyroxene megacryst. It is 4 cm long, with a large homogenous core sector and an irregular thin reaction rim with the host nepheline that is rich in Ti-magnetite microcrystals. Host nepheline shows common zoned phenocrysts of clinopyroxene and olivine (<0.4 cm).

Mineral chemical composition

Mineral chemistry has been performed by electron microprobe techniques, at the Centro Nacional de Microscopía (UCM). The analytical conditions were similar to those described in Villaseca et al. (2010). Backscattered images provide no evidence of chemical zoning in any of the main minerals of the peridotites.

Olivine

Olivine from lherzolites and harzburgite xenoliths displays similar Mg# [Mg/(Mg + Fe)] values (from 0.87 to 0.91), whereas in the wehrlite its Mg# is lower (0.83-0.86 wt%), and their contents in MnO (0.20-0.32 wt%) and CaO (0.07-0.33 wt%) are higher (Fig.1).

In the host nepheline, olivine phenocrysts are core-to-rim zoned. Core Mg# and CaO values are similar to those of the wehrlite, but olivine phenocrysts (both core and rim) have markedly lower Mn contents than in the wehrlite.

Orthopyroxene

This mineral shows a short Mg# (0.88-0.91) range, similar to that of the associated olivine. Orthopyroxene shows significant contents of Al₂O₃ (3.77-5.83 wt%), Cr₂O₃ (0.24-0.55 wt%) and CaO (0.24-1.80 wt%), also correlated with those in olivine, although within a slightly wider range.

Clinopyroxene

The Mg# values in clinopyroxene from lherzolite xenoliths range from 0.86 to 0.92 (Fig. 2A), identical to the previous described mafic phases. These values are higher than those from clinopyroxene of the wehrlite xenolith (0.85-0.88) that also contrasts by its lower Al₂O₃ and higher TiO₂ contents (Fig. 2).

Clinopyroxene in the wehrlite xenolith shows a similar chemical composition to those of megacrysts and core sectors of clinopyroxene phenocrysts of the host nepheline (Fig. 2).

Spinel and Ti-magnetite

Two types of spinel appear in the studied lherzolite xenoliths: the common primary one is characterized by low Cr₂O₃ (7.43-12.41 wt%) and high Al₂O₃ (55.44-61.59 wt%) contents, whereas the second type (only appearing in sample 115613 but showing similar textural features to primary types of the other lherzolites) shows higher Cr₂O₃ (17.36-19.41 wt%) and lower Al₂O₃ (48.15-51.09 wt%). This second spinel type shows also higher FeO (9.49-13.07 wt%) contents (Fig. 3).

Clinopyroxene in the wehrlite xenolith contains accessory Ti-magnetite, characterized by its higher TiO₂ and FeO (FeO) and lower MgO contents respect to the Ti-magnetite of the clinopyroxene megacryst rim. Moreover, its Al₂O₃ content is markedly higher than those from Ti-magnetite in the host nepheline.

Fig. 1. Mg# vs. CaO diagram of olivine in peridotite xenoliths and phenocryst from the host nepheline. See color figure in the web.

Fig. 2. A) Mg# vs. TiO₂ and B) Al₂O₃ vs. TiO₂ diagrams of clinopyroxene from peridotites, megacrysts and phenocrysts of the host nepheline. See color figure in the web.

Fig. 3. A) Al₂O₃ vs. Cr₂O₃ and B) TiO₂ vs. Cr# diagrams of spinel in lherzolites. The trend of melting of a fertile MORB mantle (FMM) is shown. See color figure in the web.

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Clinopyroxene megacryst

The studied clinopyroxene megacryst exhibits a slight compositional variation from core to its thin rim, with a systematic decrease of Mg# (0.83-0.86 to 0.74-0.81), Cr$_2$O$_3$, and Na$_2$O, and an increase of TiO$_2$ and CaO contents. Most chemical features of the clinopyroxene megacryst are recorded by the clinopyroxene phenocrysts of the host nephelinite, showing also similar core-to-rim composition (Fig. 2A).

The analyzed megacryst shows lower Mg# and Cr$_2$O$_3$, (and higher TiO$_2$) contents compared to peridotite clinopyroxene. Only the wehrlite clinopyroxene shows similar composition to those of the studied megacryst (Fig. 2B).

Geothermobarometry

The lack of garnet in the xenoliths of the Los Tormos volcano constrains pressure estimation. We have used the geobarometer proposed by Nimis and Ulmer (1998) based on clinopyroxene composition. Estimated pressure in Iherzolites and harzburgites ranges from 10 to 15.2 kbar. This pressure range is in agreement with the spinel-in-peridotite stability field (Fig. 4).

![Fig. 4: Pressure vs. temperature diagram using the geobarometer of Nimis and Ulmer (1998) and the two-pyroxene geothermometer of Brey and Kohler (1990) compared with published data (Villaseca et al., 2010). Facies boundaries for Al-rich phases in peridotite are after Gasparik (1987). See color figure in the web.](image)

Geothermometry based on the equilibrium between the two pyroxenes (Brey and Kohler 1990) has been used for the Iherzolite xenoliths. Obtained temperatures are in the range: 961-1185 °C (at assumed pressures of 10-15 kbar) (Fig. 4). Estimated P-T-values are in agreement with previous estimates in other peridotite xenolith suites of the CVF (Fig. 4).

We have also estimated pressure conditions for crystallization of the clinopyroxene megacryst and phenocrysts cores, yielding values of 10 to 14 kbar, which is within the estimated range from peridotites.

Discussion

Partial melting and depletion

Chemical composition of mafic minerals may constrain the degree of partial melting of mantle sources. On the basis of the primordial mantle composition of McDonough and Sun (1995) and mass balance of the main mineral phases of a spinel-bearing peridotite determined by Bonadiman et al. (2011) and Upton et al. (2011), it is possible to estimate the melting degree using the major element composition of pyroxenes. We have selected Al as the most robust fusible element that systematically decreases with increasing degree of partial melting undergone by the lithospheric mantle protolith.

The orthopyroxene MgO vs. Al$_2$O$_3$ diagram (Fig. 5A) suggests slightly higher melt extraction for harzburgite (up to 15%) than for Iherzolite xenoliths (up to 10%). The clinopyroxene composition (Fig. 5B) indicates similar low partial melting values (up to 10%), except one analysis that yields higher values (15%). However, Cr# vs. TiO$_2$ diagram for spinel in Iherzolite xenoliths (Fig. 5C) mostly displays low partial melting degree (< 5%), except for one sample (10%).

The studied peridotites represent fragments of a mantle domain that underwent a moderate degree of partial melting, in a range similar to those obtained in other CVF peridotite suites (Villaseca et al., 2010).

Depth of extraction of mantle xenoliths

Lithospheric thickness in Central Iberia is estimated to be about 90-100 km (Fernández et al., 1998). Geochemical characteristics of the CVF magmatism indicate their provenance from an asthenospheric source region, located at depths of garnet and phlogopite stability fields (e.g., López Ruiz et al., 2002; Lierenfeld and Mattsson, 2015).

The similarity between pressures estimated for peridotite mineral equilibration and for megacryst/phenocryst crystalization (10-15 kbar) suggests the formation of mantle magma chambers of CVF melts at ca. 50 km depth. Therefore, asthenospheric ultrabasic magmas that gave rise to the CVF stalled at lithospheric mantle depths triggering some magma crystallization (i.e., clinopyroxene, amphibole? and minor olivine) (see also Dorado et al., 2016). Lately, when basaltic magma restarted its ascent towards shallower levels, it caught cumulative minerals (megacrysts/phenocrysts) and wall-rock peridotite xenoliths, all of them from comparable (or nearby) lithospheric mantle depths.

Origin of the wehrlite xenolith

Wehrlite compositions are more fertile than primordial mantle values, and their re-fertilization has been related to metasomatic events (e.g., Raffone et al., 2009). In this
process, primary orthopyroxene of the lherzolite source has to be dissolved by a metasomatic agent creating new clinopyroxene and therefore leading to a wehrlite modal composition.

The studied wehrlite xenolith has a protogranular texture with abundant olivine (72 vol.%) that shows deformation twins and smooth curvilinear boundaries. Ti-magnetite and olivine in wehrlite have different chemical composition from those of the nepheline host. Thus, the possibility of a cumulate origin for the wehrlite is unlikely. Nevertheless, the wehrlite clinopyroxene composition is closer to clinopyroxene in the host nephelineite (megacryst, phenocryst) than those from the other peridotites (Figs. 1 and 2). This likely suggests interaction with the CVF alkali-melts or a similar silica-undersaturated metasomatic agent.

Conclusions

On the basis of mineral melting models (orthopyroxene, clinopyroxene and spinel), the studied peridotite xenoliths of the Los Tornos volcano mostly record a low partial melting degree (up to 10%) whereas more refractory harzburgite indicates a higher degree of melting (about 15%).

The wehrlite xenolith has a clinopyroxene mineral chemistry that is more similar to that in the host nephelineite than to those from the other peridotite xenoliths. This suggests some type of interaction with an alkaline silica-undersaturated melt. The metamorphic texture of the xenolith is against a magmatic cumulate origin. Further geochemical data is needed to precise the origin of this xenolith.

The formation of clinopyroxene megacrysts and phenocrysts at high depths suggests the stagnation of asthenospheric magmas and the generation of lithospheric mantle chambers triggering magma crystallization (mafic cumulates). Finally, when nephelinitic magma restarts its travel towards shallower levels, it would have fragmented the resultant cumulate minerals (megacrysts) along with the wall-rocks (peridotite xenoliths).

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