

# 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-undersaturated melts that replaced primary lherzolite orthopyroxene. Similar estimated pressures for peridotite mineral equilibration and for clinopyroxene megacryst/phenocryst crystallization in the host nephelinite 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 los 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 subsaturados en sílice 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 megacristales/fenocristales de clinopiroxeno en la nefelinita sugiere la formación de cámaras magmáticas mantélicas.

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

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## 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) outstands 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; Lierenfeld 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 re-fertilization 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 me-

gacrysts. 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 endaves 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 nephelinite have been found. According to modal contents the peridotite xenoliths are classified as Iherzolite ( $n=6$ ), 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 ( $>2\text{mm}$ ), roughly equidimensional protogranular texture. One harzburgite sample shows porphyroclastic texture. Spinel has been found only in Iherzolites, 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 homogeneous core sector and an irregular thin reaction rim with the host nephelinite that is rich in Ti-magnetite microcrystals. Host nephelinite shows common zoned phenocrysts of clinopyroxene and olivine ( $<0.4\text{ cm}$ ).

## 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 Iherzolite 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).

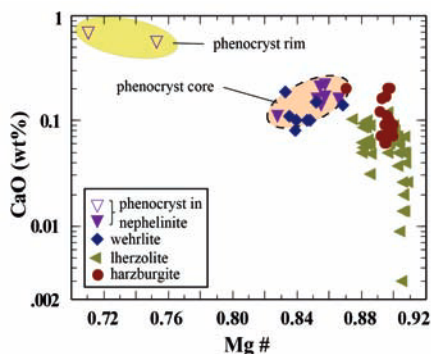


Fig. 1.- Mg# vs. CaO diagram of olivine in peridotite xenoliths and phenocryst from the host nephelinite. See color figure in the web.

Fig. 1.- Diagrama Mg# vs. CaO de olivino de las peridotitas y de fenocristales de la nefelinita. Ver figura en color en la web.

In the host nephelinite, 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  $\text{Al}_2\text{O}_3$  (3.77-5.83 wt%),  $\text{Cr}_2\text{O}_3$  (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 Iherzolite 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  $\text{Al}_2\text{O}_3$  and higher  $\text{TiO}_2$  contents (Fig. 2).

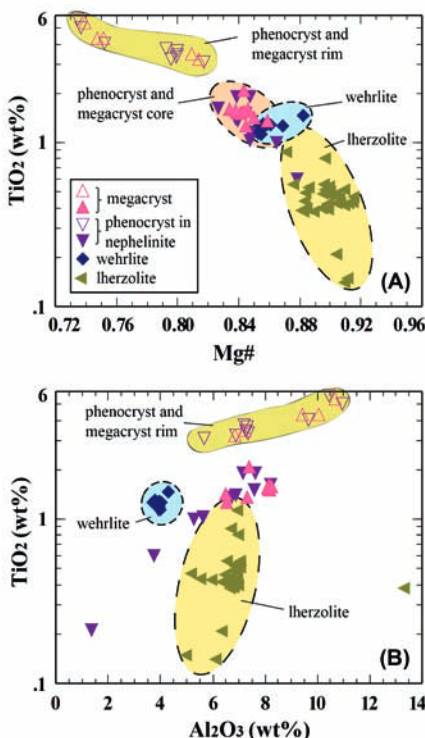


Fig. 2.- A) Mg# vs.  $\text{TiO}_2$  and B)  $\text{Al}_2\text{O}_3$  vs.  $\text{TiO}_2$  diagrams of clinopyroxene from peridotites, megacrysts and phenocrysts of the host nephelinite. See color figure in the web.

Fig. 2.- A) Diagrama Mg# vs.  $\text{TiO}_2$  y B)  $\text{Al}_2\text{O}_3$  vs.  $\text{TiO}_2$  de clinopiroxenos de peridotitas, megacrystal de clinopiroxeno y fenocristales de clinopiroxeno en la nefelinita. Ver figura en color en la web.

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

### Spinel and Ti-magnetite

Two types of spinel appear in the studied Iherzolite xenoliths: the common primary one is characterized by low  $\text{Cr}_2\text{O}_3$  (7.43-12.41 wt%) and high  $\text{Al}_2\text{O}_3$  (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 Iherzolites) shows higher  $\text{Cr}_2\text{O}_3$  (17.36-19.41 wt%) and lower  $\text{Al}_2\text{O}_3$  (48.15-51.09 wt%). This second spinel type shows also higher FeO (9.49-13.07 wt%) contents (Fig. 3).

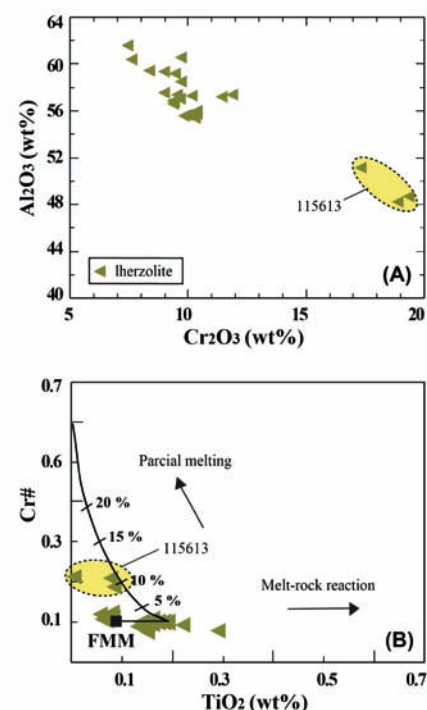


Fig. 3.- A)  $\text{Al}_2\text{O}_3$  vs.  $\text{Cr}_2\text{O}_3$  and B)  $\text{TiO}_2$  vs. Cr# diagrams of spinel in Iherzolites. The trend of melting of a fertile MORB mantle (FMM) is shown. See color figure in the web.

Fig. 3.- Diagramas A)  $\text{Cr}_2\text{O}_3$  vs.  $\text{Al}_2\text{O}_3$  y B)  $\text{TiO}_2$  vs. Cr# de espinela en Iherzolitas. Se muestra la pauta de fusión de un manto tipo MORB (FMM). Ver figura en color en la web.

The wehrlite xenolith contains accessory Ti-magnetite, characterized by its higher  $\text{TiO}_2$  and  $\text{FeO}_{\text{total}}$  and lower MgO contents respect to the Ti-magnetite of the clinopyroxene megacryst rim. Moreover, its  $\text{Al}_2\text{O}_3$  content is markedly higher than those from Ti-magnetite in the host nephelinite.

### 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),  $\text{Cr}_2\text{O}_3$  and  $\text{Na}_2\text{O}$ , and an increase of  $\text{TiO}_2$  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  $\text{Cr}_2\text{O}_3$  (and higher  $\text{TiO}_2$ ) 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 lherzolites and harzburgites ranges from 10 to 15.2 kbar. This pressure range is in agreement with the spinel-in peridotite stability field (Fig. 4).

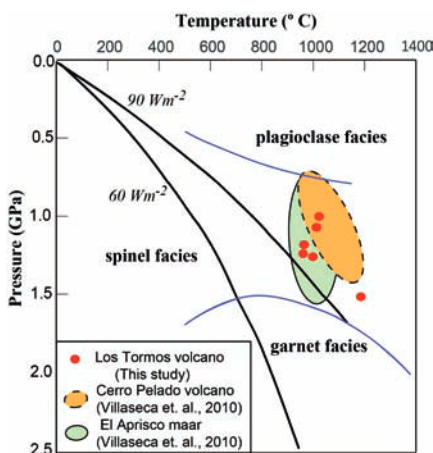


Fig. 4.- Pressure vs. temperature diagram using the geobarometer of Nimis and Ulmer (1998) and the two-pyroxene geothermometer of Brey and Kohler (1990) compared with published data (Villaseca *et al.*, 2010). Facies boundaries for Al-rich phases in peridotite are after Gasparik (1987). See color figure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

Fig. 4.- Diagrama de presión vs. temperatura, estimados usando el geobarómetro de Nimis y Ulmer (1998) y el geotermómetro de dos piroxenos de Brey y Kohler (1990). Datos de otros centros volcánicos próximos según Villaseca *et al.* (2010). Límites de estabilidad de fases ricas en Al en peridotitas según Gasparik (1987). Ver figura en color en la web.

Geothermometry based on the equilibrium between the two pyroxenes (Brey and Kohler 1990) has been used for the lherzolite 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 underwent by the lithospheric mantle protolith.

The orthopyroxene MgO vs.  $\text{Al}_2\text{O}_3$  diagram (Fig. 5A) suggests slightly higher melt extraction for harzburgite (up to 15%) than for lherzolite 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.  $\text{TiO}_2$  diagram for spinel in lherzolite xenoliths (Fig. 3B) mostly displays low partial melting degrees (< 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 phlo-

gopite 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 crystallization (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 cumulate 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

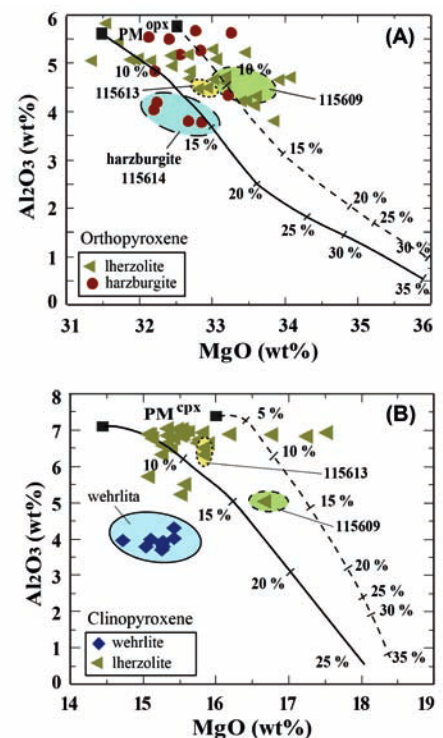


Fig. 5.- A) MgO vs.  $\text{Al}_2\text{O}_3$  diagrams for A) orthopyroxene and B) clinopyroxene showing partial melting trends of Bonadiman *et al.* (2011) (dashed) and Upton *et al.* (2011) (full line). See color figure in the web.

Fig. 5.- Diagramas MgO vs.  $\text{Al}_2\text{O}_3$  de A) ortopiroxeno y B) clinopiroxeno que muestran las tendencias de fusión parcial de Bonadiman *et al.* (2011) (línea discontinua) y Upton *et al.* (2011) (línea continua). Ver figura en color en la web.

process, primary orthopyroxene of the Iherzolite 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 nephelinite 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 nephelinite (megacryst, phenocryst) than those from the other peridotites (Figs. 1 and 2). This likely suggests interaction with the CVF alkaline 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 Tormos 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 nephelinite 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 ori-

gin. 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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