

Kaersutite megacrysts in the alkaline mafic dikes of the Panticosa pluton (Pyrenean Axial Zone, Spain): deep-origin xenocrysts

Megacrystales de kaersutita en los diques máficos alcalinos del plutón de Panticosa (Zona Axial Pirenaica): xenocrystales de origen profundo

Pablo Tierz, Marceliano Lago, Carlos Galé, Enrique Arranz, Teresa Ubide, Patricia Larrea and Tomás Sanz

Departamento de Ciencias de la Tierra. C/ Pedro Cerbuna 12, 50009 Zaragoza, España.

pablo.tierz.lopez@gmail.com, mlago@unizar.es, carlos.gale@gmail.com, earranz@unizar.es, tubide@unizar.es, plarreamarquez@gmail.com, tomassanzserrano@gmail.com

ABSTRACT

Megacrysts of kaersutite have been identified in several alkaline mafic dikes from the Panticosa pluton. They show strongly anhedral habits and resorption features, including Krs overgrowths and/or Cpx-Opq coronae. Chemically, the liquid in equilibrium with the megacryst cores is clearly different from the host alkaline dikes. In contrast, the liquid in equilibrium with Krs overgrowths and Cpx from the coronae agrees with the composition of some of the host alkaline dikes. According to the obtained results, Krs megacrysts must be considered xenocrysts. Therefore, their Middle Permian age (268 Ma) predates the emplacement of the alkaline dikes. The xenocrysts crystallised at about 30 km depth and were afterwards reequilibrated at lower depths.

Key-words: Kaersutite, dike, alkaline, Permian, Pyrenees.

Geogaceta, 52 (2012), 45-48.
ISSN 2173-6545

RESUMEN

En los diques máficos alcalinos del plutón de Panticosa se han identificado megacrystales de kaersutita. Muestran hábitos anhedrales y características típicas de reabsorción, así como recrecimientos de Krs y de una corona de Cpx y Opq. Los fundidos en equilibrio con los núcleos de Krs son muy distintos de los diques alcalinos que los contienen, mientras que los fundidos en equilibrio con los recrecimientos de Krs y los Cpx de las coronas son similares a algunos de los diques. Por lo tanto, los megacrystales de Krs son xenocrystales y su edad, Pérmico Medio (268 Ma), es previa a la edad de emplazamiento de los diques. Los xenocrystales se formaron a unos 30 km de profundidad y se reequilibraron a menor profundidad.

Palabras clave: Kaersutita, dique, alcalino, Pérmico, Pirineos.

Fecha de recepción: 14 de febrero de 2012
Fecha de revisión: 26 de abril de 2012
Fecha de aceptación: 25 de mayo de 2012

Introduction

The Panticosa pluton is the southernmost part of the Panticosa-Cauterets complex (Pyrenean Axial Zone) (Fig. 1). It is considered late-Carboniferous in age (301 ± 7 Ma; Ternet *et al.*, 2004); therefore, it is synkinematic to the main deformational phase of the European Variscan Orogeny (Gleizes *et al.*, 1998). Several mafic dikes cut the Panticosa pluton and its country rocks.

The mafic dikes are centimetric to metric in width and metric to kilometric in length and can be divided into two groups (Tierz *et al.*, in press): a N-S trending calc-alkaline dike system and a E-W trending alkaline dike system, which cuts the former (Gil-Imaz *et al.*, 2012). These rocks are classified as lamprophyres and diabases.

The alkaline dikes are doleritic to mi-

crophyritic and consist of microcrysts and phenocrysts of plagioclase (Pl: 40-70%) and Ti-rich clinopyroxene (Cpx: 10-30%), olivine pseudomorphs (Ol: 3-10%), biotite (Bt: 1%) and titanite (Ttn: 1%) (mineral abbreviations in this work follow recommendations by Whitney and Evans, 2010). Vesicles, sometimes important (up to 10%), are filled by chlorite \pm calcite.

Coarse-grained constituents have been observed in some alkaline dikes, namely: macrocrysts or megacrysts of Ti-rich amphibole (Amp), opaque minerals (Opq), apatite (Ap) and/or biotite, and enclaves with diverse mineral assemblages. The enclaves are always formed by large Pl crystals and occasional large Ti-rich Amp or Bt crystals. The Amp megacrysts were dated as 268 ± 7 Ma by Debon and Zimmermann (1993).

Our present work focuses on the petrological features and chemical composition (including major and trace elements) of the Amp megacrysts. The whole-rock composition of the host alkaline dikes will be used for comparison.

Characterisation of the amphibole megacrysts

Petrography

The studied Amp megacrysts are dark brown to black to the naked eye and brown-coloured under plane polarised light. They show rounded, reniform or amoeboid shapes and 3-4 cm average size (up to 8 cm). In addition to their anhedral habit, megacrysts show partial resorption features (Fig. 2), including Cpx-Opq coro-

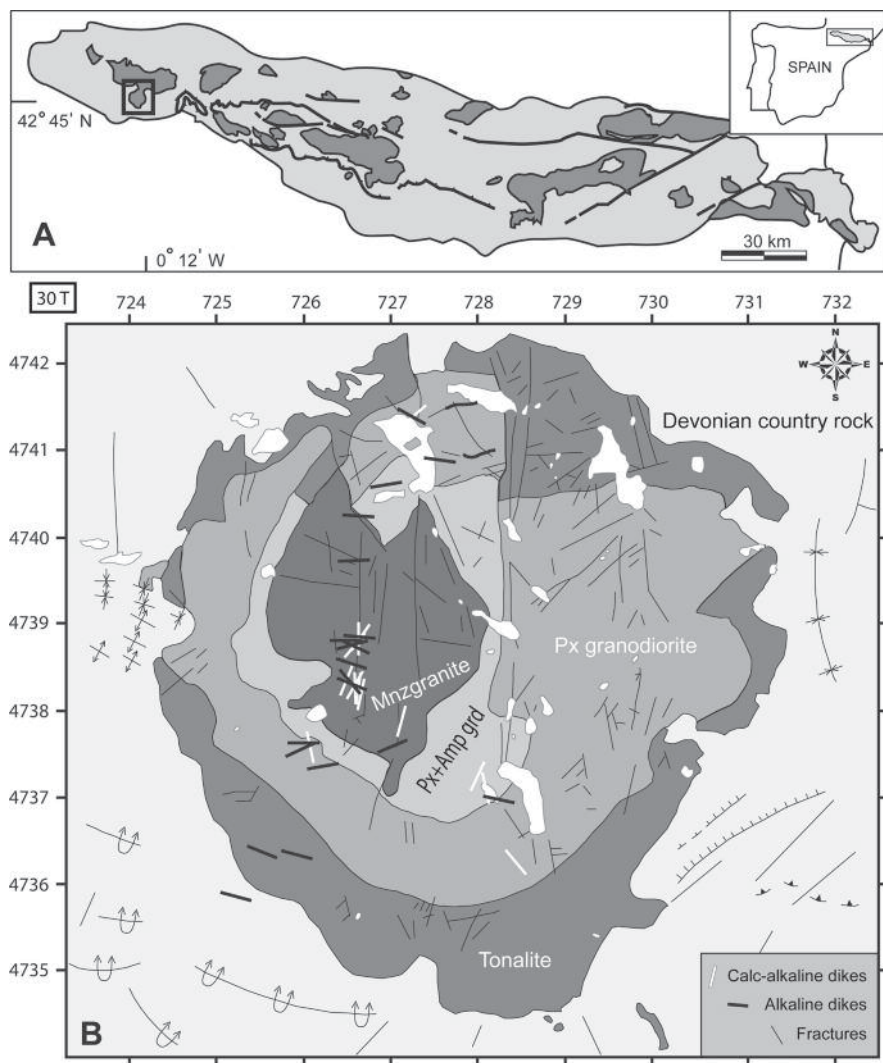


Fig. 1.- A) Simplified map of the Pyrenean Axial Zone, including the location of the Panticosa pluton (black square). B) Geological map of the Panticosa pluton referenced to the UTM coordinate system.
 Fig. 1.- A) Mapa sintética de la Zona Axial Pirenaica en el que se incluye la localización del plutón de Panticosa (cuadrado negro). B) Mapa geológico del plutón de Panticosa, referenciado en coordenadas UTM.

nae which mark previous megacryst habits, slightly jagged rims and permeated zones filled by host rock groundmass. Some of the megacrysts also display Amp overgrowths. These textural features suggest that the Amp megacrysts could not crystallise in equilibrium with the host rock groundmass.

Chemical composition

Major element concentrations of ten different Amp megacrysts were obtained using a JEOL JXA-8900M electron microprobe at the Centro Nacional de Microscopía Electrónica of the Universidad Complutense de Madrid. Analyses include Amp cores, Amp overgrowths and Cpx coronae. Moreover, the trace element composition of an Amp megacryst core was analysed using

a Mercantek UV-213 Laser coupled to a quadrupole AGILENT 7500a ICP-MS at the Centro de Instrumentación Científica of the Universidad de Granada.

The major element composition of Amp cores, Amp overgrowths and Cpx coronae is presented in Table I. Both Amp cores and overgrowths are calcic Amp, classified as kaersutite (Krs) according to Leake *et al.* (1997) criteria. Cpx coronae are classified as Al-rich diopside according to Morimoto *et al.* (1988) criteria.

Amp cores are rather homogeneous in composition. However, three main groups can be defined according to the small variations in the mg# content [Mg / (Mg + Fe²⁺ + Fe³⁺ + Mn + Ni) per formula unit; p.f.u.]: 1) mg#: 0.57-0.64; 2) mg#: 0.55-0.57; 3) mg#: 0.49-0.50.

Amp overgrowths exhibit less homogeneous compositions than Amp cores. They are enriched in TiO₂ and depleted in K₂O compared to the cores (Fig. 3), indicating lower pressures of crystallisation (Adam and Green, 1994). Moreover, Amp overgrowths display higher mg# values than Amp cores.

Cpx coronae show variable compositions. It is noticeable their moderate TiO₂ contents and high mg# values. The latter are clearly greater than those of the Amp megacryst cores and similar to the Amp megacryst overgrowths (Table I).

Mineral phases	Amp Cores (67)	Amp Rims (17)	Cpx coronae (22)
SiO ₂ (wt%)	39.31	38.44	48.84
TiO ₂	5.95	7.40	2.04
Al ₂ O ₃	13.02	13.76	4.54
MgO	10.66	12.50	13.54
FeOt	13.74	9.94	7.87
CaO	10.82	11.93	22.08
Na ₂ O	2.74	2.47	0.48
K ₂ O	1.20	0.95	—
mg#	0.49-0.64	0.66-0.74	0.69-0.77
(Mg/Fe) _{eq}	0.56	1.08	1.18

Table I.- Average compositions and in equilibrium liquid Mg/Fe ratios for Amp megacryst cores and rims and for Cpx coronae. Numbers in parentheses indicate the number of analyses.

Tabla I.- Composiciones promedio y ratios Mg/Fe para los líquidos en equilibrio con núcleos y bordes de megacristales de Amp, y con las coronas de Cpx. Números en paréntesis indican el número de análisis.

According to quantitative thermobarometric calculations based on the Otten (1984) thermometer and two different barometers (Johnson and Rutherford, 1989; Schmidt, 1992), the obtained temperature values for megacrysts cores range from 1045 °C to 1076 °C whilst pressure conditions are estimated to be between 6.9 and 9.7 kbar, implying a 26-34 km depth.

An Amp megacryst from the intermediate mg# group (sample PAN-MX3D) was selected for trace element analyses. Several analyses in the core of the crystal yielded highly similar results. Total REE concentrations (ΣREE) are clearly high: 642 to 938 ppm. The primitive mantle-normalised (McDonough and Sun, 1995) REE patterns are convex-upwards, with greater enrichment in LREE compared to HREE. The normalised multielemental diagrams show positive anomalies in Ba and Nb-Ta, while the most important negative anomalies correspond to Rb, Th, U and Pb.

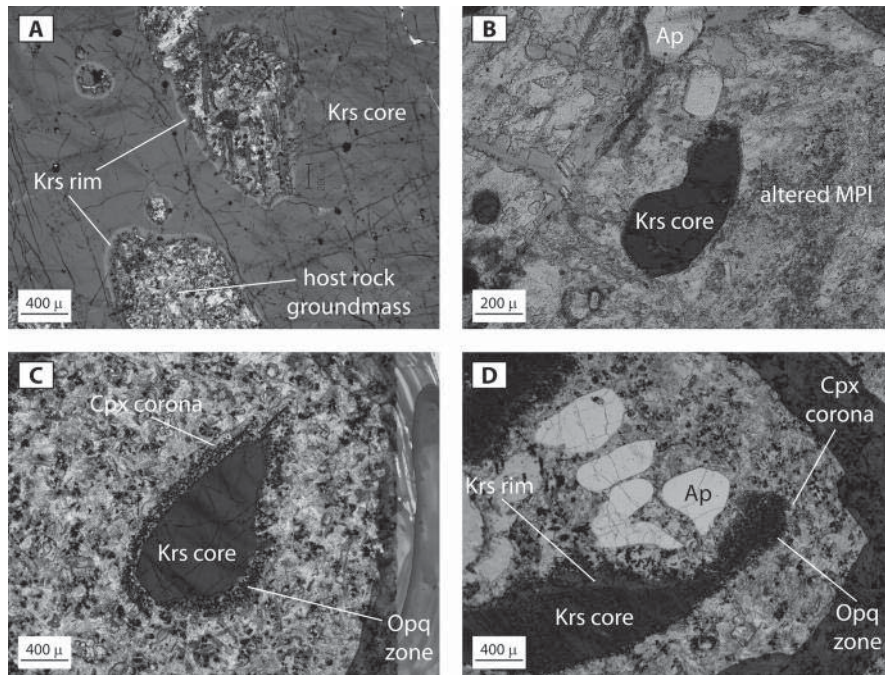


Fig. 2.- Microscope images from Krs megacrysts of the mafic alkaline dikes of the Panticosa pluton. A) Krs megacryst core with Krs rim. It can be seen some permeated zones. B) Krs macrocryst inside an enclave. C) Krs megacryst core with Cpx-Opq corona. D) Strongly anhedral Krs megacryst core with Krs rim and Cpx-Opq corona.

Fig. 2.- Imágenes de microscopía de los megacristales de Krs de los diques máficos alcalinos del plutón de Panticosa. A) Núcleo de megacristal de Krs con borde de Krs. Se observan algunas zonas permeadas. B) Macrocrystal de Krs dentro de un enclave. C) Núcleo de megacristal de Krs con corona de Cpx-Opq. D) Núcleo de megacristal de Krs, fuertemente alotriomorfo, con borde de Krs, corona de Cpx-Opq.

Megacrysts/host magma relationship

We have calculated the molar fraction Mg/Fe of the liquid in equilibrium with the three different types of Amp megacrysts cores using a partition coefficient $Kd_{liq-Amp}^{(Mg-Fe)} = ([Mg_{liq} \cdot Fe_{Amp}] / [Mg_{Amp} \cdot Fe_{liq}])$ of 0.38 (LaTourrette *et al.*, 1995). The calculated Mg/Fe values of the liquids in equilibrium are 0.64 ± 0.04 , 0.52 ± 0.01 and 0.39 ± 0.01 . Meanwhile, the whole-rock Mg/Fe ratios of the host dikes can be divided into four groups: 1) less fractionated rocks: 3-4.5; 2) slightly more fractionated rocks: 1.64-1.67; 3) moderate alkaline and Ti-rich rocks: 1.2; and 4) fractionated rocks: 0.72. None of these values is in agreement with the Mg/Fe ratios of liquids in equilibrium with the Amp megacryst cores.

The trace element composition of the liquid in equilibrium with the PAN-MX3D megacryst core has been also calculated using the partition coefficients ($D_{Amp-liq}^{(Mg-Fe)}$) provided by Fulmer *et al.* (2010) for Krs. The liquid in equilibrium with the

megacryst core shows relative fractionated patterns ($[La/Lu]_N = 5.4$). The primitive mantle – normalised multielemental diagram (Fig. 4) shows enrichments in the highly incompatible elements, small negative anomalies in Sr and Rb and a positive anomaly in Nb-Ta. No relationship can be established between the liquid in equilibrium with the megacryst and the host alkaline dikes, in agreement with the results of the Mg-Fe exchange.

The Mg/Fe ratios of the liquids in equilibrium with Amp overgrowths and Cpx coronae have also been calculated; the partition coefficient for Cpx ($Kd_{liq-cpx}^{(Mg-Fe)}$) has been considered 0.26 (Akinin *et al.*, 2005). The obtained results are 1.02 ± 0.12 for the Amp overgrowths and 1.18 ± 0.19 for the Cpx coronae. These values are similar to each other and clearly distinct from those obtained for the megacryst cores. The liquids in equilibrium with Amp overgrowths and Cpx coronae agree with the moderate alkaline and Ti-rich host rocks, suggesting that both types of rims crystallised from these type of magmas.

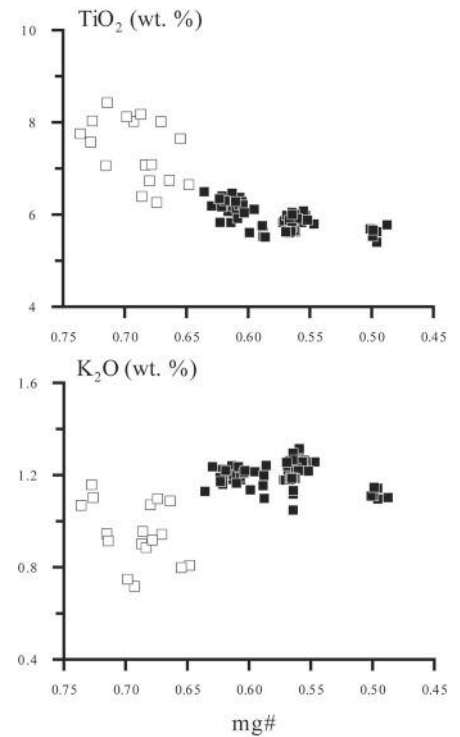


Fig. 3.- Top: TiO₂ vs mg# diagram for Krs megacrysts. Bottom: K₂O vs mg# diagram. Black squares: megacryst cores; white squares: megacryst rims.

Fig. 3.- Arriba: diagrama TiO₂ vs mg# de los megacristales de Krs. Abajo: Diagrama K₂O vs mg#. Cuadrados negros: núcleos; cuadrados blancos: bordes de los megacristales.

Discussion

All the presented data point to a non-cogenetic origin for the Amp (Krs) megacryst cores of the mafic alkaline dykes from the Panticosa pluton. Therefore, these megacrysts must be considered xenocrysts. They crystallised from alkaline and relatively fractionated magmas (Mg/Fe = 0.77-0.38), at an approximate depth of 30 km. According to the compositional homogeneity of the megacryst cores, with small differences in mg#, the three types of megacryst cores could define successive fractionation stages in a magmatic system.

The megacryst cores were later included into a different magma batch, triggering resorption of the cores (Fig. 2). Moreover, two different megacryst rims were developed in equilibrium with the new magma: Amp overgrowths and Cpx-Opq coronae. According to the Ti and K contents p.f.u. in Amp overgrowths, they may crystallise at shallower levels than the cores. In addition, the Ti, K and Na contents p.f.u. of Cpx microcrysts in the coronae are compatible with

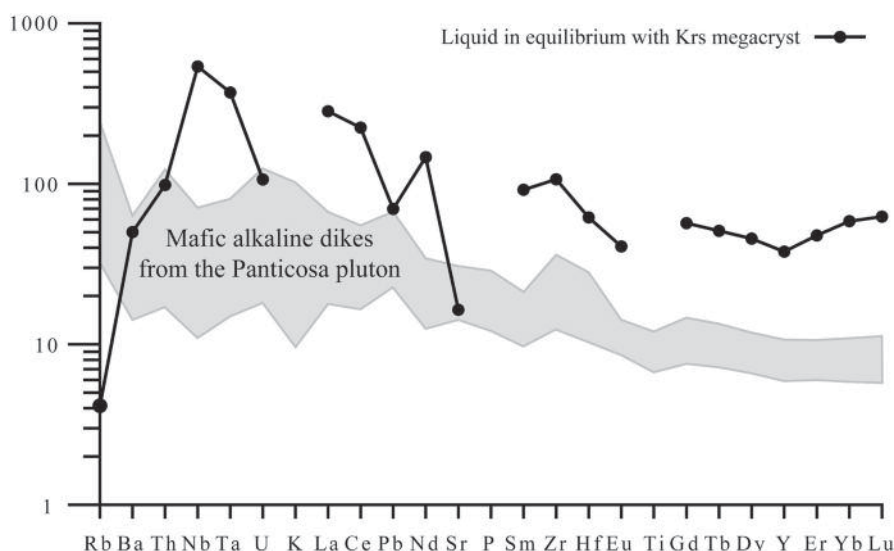


Fig. 4.- Multielemental, normalised to primitive mantle (McDonough and Sun, 1995) diagram for the mafic alkaline dikes of the Panticosa pluton and for the liquids in equilibrium with the Krs megacrysts (D values taken from Fulmer *et al.*, 2010).

Fig. 4.- Diagrama multielemental, normalizado respecto a manto primitivo (McDonough y Sun, 1995) para los diques máficos alcalinos del plutón de Panticosa y para los líquidos en equilibrio con los megacrystales de Krs (valores de D tomados de Fulmer *et al.*, 2010).

their crystallisation from a moderately alkaline magma, similar to some of the studied dikes.

If a xenocrystic origin is assumed for the studied megacrysts, their calculated age (268 ± 7 Ma; Debon and Zimmermann, 1993) cannot be considered the age of emplacement of the alkaline dikes (e.g. Orejana *et al.*, 2006; Denèle *et al.*, 2011). In consequence, the studied dikes are not Middle Permian in age but probably younger. In agreement with this hypothesis, a Late Permian age (259 ± 3.2 Ma) has been recently reported for an alkaline dolerite dike cutting the metasedimentary country-rocks of the Panticosa pluton (Rodríguez *et al.*, 2011).

Conclusions

Megacrysts of Ti-rich Amp (Krs) are found in some alkaline mafic dikes of the Panticosa pluton. They show anhedral, rounded or amoeboidal habits, evidence of partial resorption and Amp overgrowths and/or Cpx-Opq coronae.

The major and trace element composition of the megacryst cores is very homogeneous. However, three groups can be dis-

tinguished on the basis of their mg# contents. Trace element concentrations are very high, especially for the highly incompatible elements.

Megacryst cores probably crystallised under high pressures (ca. 8 kbar, 30 km depth) and were recrystallised or reequilibrated at lower depths.

According to the major and trace element results, the megacrysts do not bear any genetic relation with their host dikes. Therefore, the Krs megacrysts are xenocrysts. Accordingly, the Middle Permian age obtained by Debon and Zimmermann (1993) cannot represent the age of emplacement of the alkaline dikes, but the previous crystallisation of the Krs megacrysts in depth.

The emplacement age of the alkaline mafic dikes of the Panticosa pluton must be reconsidered. It may be Late Permian or even younger.

Acknowledgements

This work is part of the project CGL2011-27477. We want to thank David Orejana and Juan Díaz Alvarado for their constructive reviews.

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