Cumulate origin of the Alkaline Xenoliths from Graciosa Island (Açores, Portugal): geochemical modelling

Origen acumulado de los xenolitos alcalinos de la Isla Graciosa (Azores, Portugal): modelización geoquímica

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RESUMEN

En este trabajo se ha comparado la composición en REE de los xenolitos alcalinos objeto de estudio y las lavas de la Unidad del Vulcão Central de la isla Graciosa (Azores). Dada la similitud composicional entre ambos, se han desarrollado dos modelos geoquímicos, tanto para elementos mayores (MELTS) como para tierras raras (hoja de cálculo ad-hoc), con el objetivo de estudiar el proceso genético que los relaciona. En ambos casos, se ha conseguido derivar mediante un proceso de cristalización fraccionada, a partir de la lava menos diferenciada de la Unidad del Vulcão Central, la composición de un xenolito alcalino representativo del resto. Los resultados obtenidos indican que los xenolitos serían los acumulados de cámara magmática y las coladas basálticas de la Unidad del Vulcão Central, los fundidos extruidos resultado del proceso de cristalización fraccionada.

Palabras clave: *Xenolito, alcalino, MELTS, Graciosa, Azores.*

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Introduction

The Graciosa Island belongs to the Central Group of the Azores archipelago, between 39º and 39º06’ N latitudes and 27º56’ and 28º05’ W longitudes. It is located within the Azorean microplate, a topographic high near the Mid Atlantic Ridge (MAR), bordered by the Eurasian, African and American plates (Fig. 1A).

The island is formed by volcanic rocks that range from basalts to trachytes. Gaspar (1996) recognized three major volcanic complexes (Fig. 1B), in order of decreasing age: the Serra das Fontes Volcanic Complex (SFVC), the Serra Branca Volcanic Complex (SBVC) and the Vitória-Vulcão Central Volcanic Complex. The latter comprises two contemporaneous units: the Vitória Unit (VU) and the Vulcão Central Unit (VCU).

The petrology and composition of the Graciosa xenoliths were the focus of preliminary studies (Larrea *et al*., 2010a-in press-, b and c). In this work we compare the whole rock composition of alkaline xenoliths from the VCU, with previously published compositions for their host basalts (Almeida, 2001). We

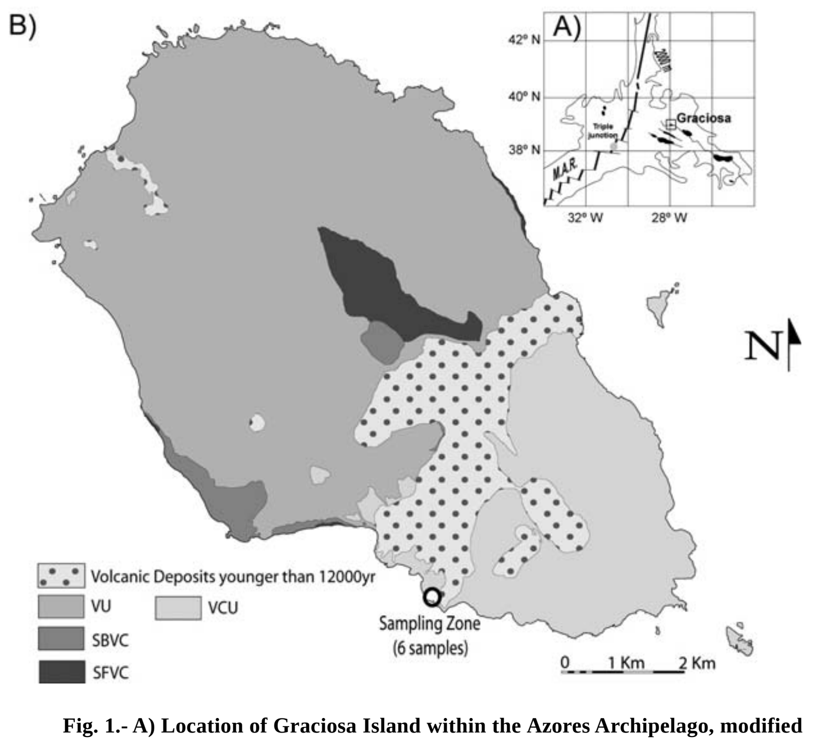

Fig. 1.- A) Location of Graciosa Island within the Azores Archipelago, modified from França *et al.* (2006), M.A.R.: Middle Atlantic Ridge; B) Volcanological map of Graciosa, modified from Gaspar (1996).

Fig. 1.- A) Localización de la isla Graciosa en el Archipiélago de Azores, modificado de França* et al. *(2006), M.A.R.: Dorsal Medio Atlántica; B) Mapa vulcanológico de Graciosa, modificado de Gaspar (1996).

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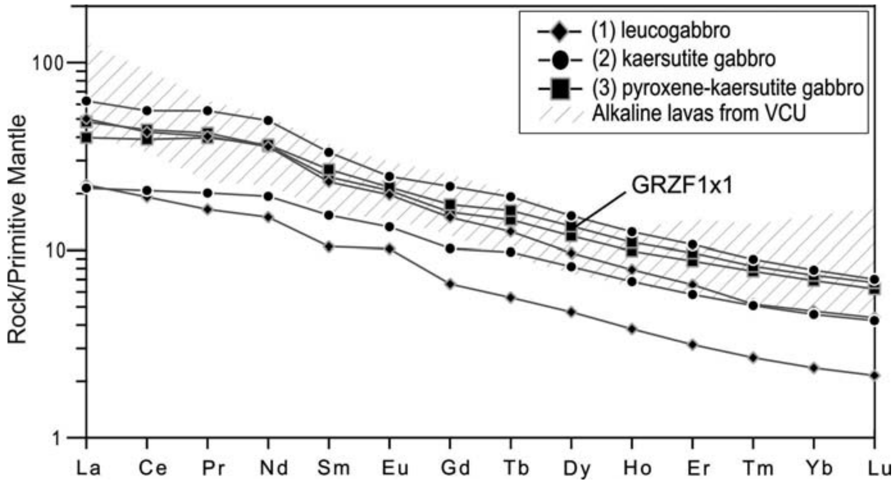

Fig. 2.- Primitive mantle (McDonough and Sun, 1995) normalized REE patterns of the alkaline xenoliths and lavas from the VCU.

Fig. 2.- Pautas de REE de los xenolitos y las lavas alcalinas de la VCU normalizadas a la composición de un manto primitivo (McDonough and Sun, 1995).

present the first modelling on gabbroic alkaline xenoliths in Azores, in order to establish their origin.

Materials and methods

Six alkaline enclaves were sampled from a basaltic lava flow within the VCU (Fig. 1B). They are 5 to 30 cm long and show sub-rounded shapes and sharp contacts. A discontinuous reaction rim between the xenoliths and the host basalt has been recognized. Where plagioclase or pyroxene are in contact with the basalt a clear contact appears; in contrast, a large rim is observed between amphibole crystals and the basalt. This rim is 200 to 400 µm in size: it is composed of allotriomorphic olivine, pyroxene, plagioclase, ilmenite and Ti-magnetite.

Sample preparation was carried out at the University of Zaragoza. Whole rock major and trace element concentrations were determined by ICP-MS in the Ibercron laboratory (University of the Basque Country). Further details on analytical methods can be found on García de Madinabeitia *et al.* (2008).

Petrology

Gabbroic alkaline xenoliths in the VCU are composed of different proportions of olivine, clinopyroxene, kaersutite, plagioclase, Fe-Ti oxides and F-rich apatite, resembling xenoliths from other Azorean islands. Their cumulate texture suggests that the xenoliths are magma chamber cumulates; the different xenolith types may reflect the chamber zoning.Olivine shows two different compositional groups, Fo78-68 and Fo57-53, analysed in the same sample. The most magnesian compositions occur either as inclusions or interstitial crystals. Clinopyroxene crystals are diopside and augite, showing a wide fractionation range (Fs8-17) and high TiO2 values (up to 2.7%), in agreement with the alkaline affinity of the rock. Plagioclase displays a range of compositions between An76 and An49; the Or molecule increases towards the andesine terms, indicating an alkaline trend. All xenoliths contain kaersutite with little compositional variations (mg#: 0.7-0.6).

Geochemistry

According to their composition, the xenoliths are classified as alkaline gabbros, with the following contents in SiO2 (41.8-47.3%), MgO (10.5-3.4%), Na2O+K2O (3.0-4.1%), TiO2 (2.4-5.1%), P2O5 (0.3-4.6%), Ta (1.2-2.9ppm) and Nb/Y (0.9-1.1) relations.

Phases /Tª	1295	1270	1250	1230	1210	1190	1170	1150	1130	1110	1090	1070	1050	1030	1010	990	970	950	930
Ol	--	100	100	100	100	35	**24**	19	18	18	18	18	18	18	18	19	19	19	18
Cpx	--	--	--	--	--	65	**70**	60	52	45	40	36	33	31	29	27	26	25	25
Pl	--	--	--	--	--	--	**4**	10	15	18	21	24	26	28	29	30	31	32	33
Amp	--	--	--	--	--	--	**2**	10	15	18	20	21	21	22	22	22	22	22	22
Ap	--	--	--	--	--	--	**--**	--	--	1	1	1	1	1	1	1	1	1	1
Op	--	--	--	--	--	--	**--**	--	--	--	--	--	--	1	1	1	1	1	1
% Liquid	100	98	96	94	92	70	**58**	43	32	25	20	15	12	10	8	7	6	2	0
SiO_2 liq.	46,67	46,87	47,01	47,14	47,28	47,00	**47,65**	49,46	51,10	52,51	53,64	54,59	55,35	55,85	56,17	56,32	56,33	56,24	0,00
TiO_2 liq.	3,05	3,13	3,19	3,25	3,30	3,58	**3,35**	2,72	2,28	1,95	1,68	1,48	1,26	1,07	0,90	0,74	0,61	0,44	0,00
Na_2O liq.	3,01	3,09	3,15	3,20	3,26	4,16	**4,74**	5,51	6,47	6,38	6,53	6,54	6,54	6,53	6,51	6,51	6,51	7,67	0,00
K_2O liq.	1,01	1,04	1,06	1,08	1,09	1,45	**1,74**	2,28	2,86	3,44	3,99	4,58	5,00	5,31	5,53	5,68	5,77	4,67	0,00

Table I.- Summary of the data obtained by a fractional crystallization model using the MELTS software (Asimow and Ghiorso, 1998; Ghiorso and Shack, 1995).

Tabla I.- Resumen de los datos obtenidos mediante un modelo de cristalización fraccionada con el software MELTS (Asimow and Ghiorso, 1998; Ghiorso and Shack, 1995).

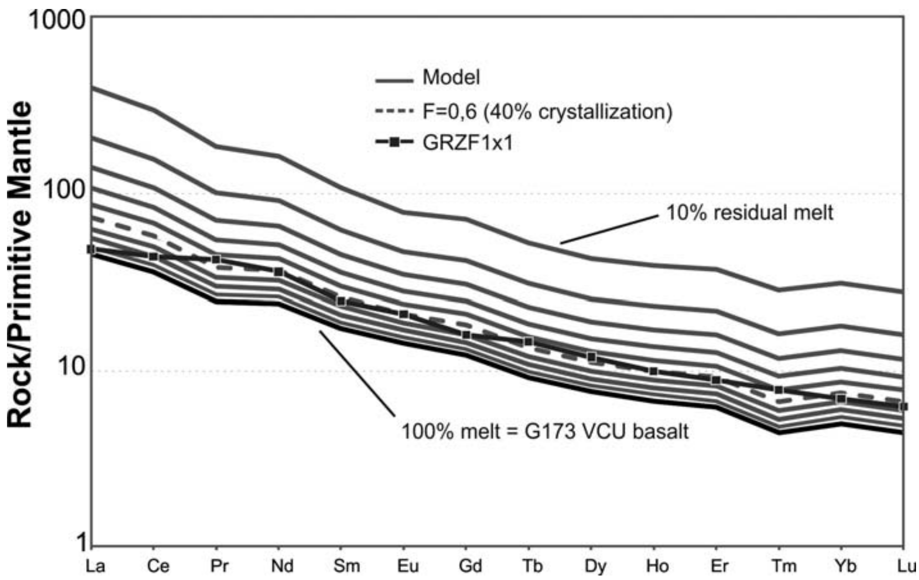

Fig. 3.- Primitive mantle (McDonough and Sun, 1995) normalized REE patterns of the fractional crystallization model for the G173 lava.

Fig. 3.- Pautas de REE del modelo de cristalización fraccionada a partir de la lava G173, normalizadas a la composición de un manto primitivo (McDonough and Sun, 1995).

Taking into account their petrographical and compositional features, these gabbros can be divided into three groups: (1) leucogabbros, (2) kaersutite gabbros and (3) pyroxene-kaersutite gabbros (Larrea *et al*., 2010b and c).

The REE patterns of the six studied xenoliths are rather parallel and enriched, with La/LuN: 5.2-11.9 (Fig. 2). Moreover, VCU basalts hosting the studied xenoliths (Almeida, 2001) display alkaline REE patterns, in agreement with those of the xenoliths (Fig. 2). Therefore, the magmas generating the alkaline xenoliths and the basalts may be related. Due to the cumulate origin of these xenoliths, they were probably formed by a fractional crystallization process; on the other hand, the basalts may represent the extruded melts generated in that crystallization process.

Fractional crystallization models

In order to prove this hypothesis we present two different approaches: i) using major element compositions and ii) via minor trace element contents.

In both cases, the most primitive available lava (G173; Almeida, 2001) has been used as the closest composition to the primary magma. It has 10.07% MgO, 8.05% FeO, 46.07% SiO2, 230 ppm Ni and 517 ppm Cr. On the other hand, the model has been calculated for the GRZF1x1 xenolith (Fig. 2) which represents an intermediate composition being more evolved than the G173 lava; thus this composition cannot be the result of the first crystallization stages of G173 lava.

i) The major element model has been done using the MELTS software (Asimow and Ghiorso, 1998; Ghiorso and Shack, 1995). The fractionation process starts at 5 kbar (approx. 16.5 km depth; Beier *et al*., 2006); in these conditions MELTS calculates a liquidus temperature of 1295 ºC for sample G173. The results obtained from the fractional crystallization process are summarized in table I, where the fractionated mineral phases, the percentage of remaining liquid and its composition in weight percent of oxides are shown for each temperature stage.

The results show that a minimum crystallization of 40% is needed to start crystallizing Pl and Amp. At these conditions (1170ºC) the composition of the residual melt is similar to that of GRZF1x1 xenolith -SiO2 (44,85%), TiO2 (2,35%), Na2O (3,56%) and K2O (0,54%)-. These data indicate that the studied xenoliths are the crystallization product of a rather evolved liquid.

Therefore, we can derivate the composition of one representative alkaline xenolith from the most primitive lava composition of the VCU, through a fractional crystallization process.

ii) Modeling the Rare Earth elements (REE) has been developed with a spreadsheet based on the mathematical equation for a fractional crystallization process (Rayleigh, 1896):

$$CL = Co \bullet F^{(D-1)}$$

Where Co is the concentration of an element in the initial magma, F is the fraction of remaining magma, D is the global partition coefficient, calculated with the partition coefficient of the element for each fractionated mineral (Zack & Brumm, 1998; Skulski *et al*., 1994; McKenzie & O'Nions, 1991; Lemarchand *et al*., 1987; Paster *et al*., 1974) and with the percentages of fractionated minerals in the major element model (24% Ol, 70% Cpx, 4% Pl, 2% Am), and CL is the concentration of the element in the remaining liquid that would crystallize for a given F and D.

Figure 3 shows agreement between the xenolith and the model at a rate of 40% of crystallization (60% of remaining magma), as it has been observed in the major element model. This result also suggests that the xenoliths and the host basalts are related by a fractional crystallization process, based on the similarity of their REE's patterns (Figs. 2 and 3).

Conclusions

Xenoliths hosted in a basaltic lava of the Vulcão Central Unit are alkaline gabbros; they can be divided in three groups.

Mineral chemistry and geochemical composition reveals the alkaline affinity of these xenoliths. Their REE patterns are similar to each other and to the alkaline host basalts. Therefore, it is likely that the xenoliths and their host basalts have a common origin and are related by a fractional crystallization process.

In order to demonstrate that hypothesis two models, based on major and REE elements, have been developed. In both cases, it is possible to reproduce the composition of one representative xenolith starting from the composition of the most primitive lava of the VCU.

Hence, xenoliths and VCU lavas were probably generated in a common magma chamber. The former may represent the cumulate phases, while the latter might correspond to the extruded melts resulting from the fractional crystallization process.

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References

Almeida M.H. (2001). *A fonte mantélica na região dos Açores: constrangimentos impostos pelas característicsa geoquímicas de rochas vulcânicas e de xenolitos ultramáficos*. Ph. D. Thesis, Univ. dos Açores, 184 p.

Asimow, P.D. and Ghiorso, M.S. (1998). *American Mineralogist*, 83, 1127-1131.

Beier, C., Haase, K.M. and Hansteen, T. H. (2006). *Journal of Petrology*, 47 (7), 1375-1411.

García de Madinabeitia S., Sánchez-Lorda, M.E. and Gil-Ibarguchi, J.I. (2008). *Analytica Chimica Acta*, 625, 117-130.

Gaspar J.L. (1996). *Ilha Graciosa (Açores): História Vulcanológica e Avaliaçao do Hazard*. Ph. D. Thesis, Univ. dos Açores, 361 p.

Ghiorso, M.S. and Sack, R.O. (1995). *Contributions to Mineralogy and Petrology*, 119, 197-212.

França, Z., Lago, M., Nunes, J.C., Galé, C., Forjaz, V. H., Pueyo, O. and Arranz, E. (2006). *Geogaceta*, 40, 87-90.

Larrea, P., Lago, M., França, Z., Widom, E., Galé, C., Ubide, T. and Arranz, E. (2010a). *Geogaceta*, 48, 155-158.

Larrea, P., Lago, M., França, Z., Widom, E., Galé, C., Ubide, T. and Arranz, E. (2010b). *Macla*, 13, 131-132.

Larrea, P., Lago, M., França, Z., Widom, E., Galé, C., Ubide, T. and Pueyo, O. (2010c). *Macla*, 13, 133-134.

Lemarchand, F., Benoit, V. and Calais, G. (1987). *Geochimica et Cosmochimica Acta*, 51, 1071-1081.

McDonough, W.F. and Sun, C.C. (1995). *Chemical Geology*, 120, 223-253.

McKenzie, D. and O'Nions, R.K. (1991). *Journal of Petrology*, 32, 1021-1091.

Paster, T.P., Schauwecker, D.S. and Haskin, L.A. (1974). *Geochimica et Cosmochimica Acta*, 38(10), 1549-1577.

Rayleigh, J.W.S. (1896). *Philosophical magazine*, 42, 77-107.

Skulski, T., Minarik, W. and Watson, E. B. (1994). *Chemical Geology*, 117(1-4), 127-147.

Zack, T. and Brumm, R. (1998). In: 7th International Kimberlite Conference. Red Roof Design, Cape Town, South Africa, 986-988.